A Final Report

Contract No. N0014-78-C-0695

DISCRETE ANALOG PROCESSING FOR TRACKING AND GUIDANCE CONTROL

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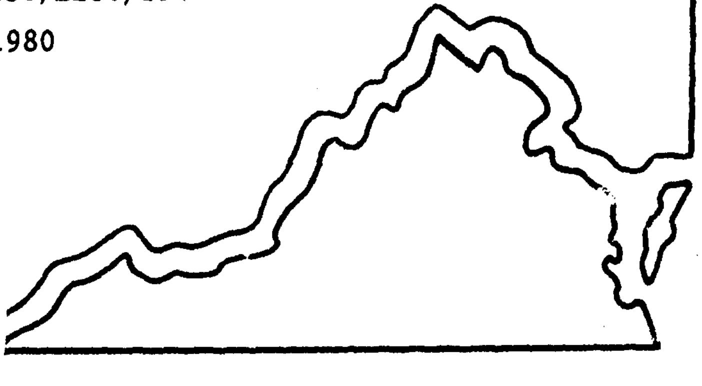
Report No. UVA/525350/EE80/104

November 1980



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Implementation of the Taylor Series Video Image Processing (TSVIP) algorithm for tracking and guidance is presented using an HP 2100 digital computer to solve the equation. Closed loop system operation was achieved using a Reticon 100 x 100 matrix photodiode camera, a microprocessor controlled A/D converter as an interference to supply signals to the computer and pan tilt servoes operating from computer generated signals to control camera position. Tentative studies of CCD implementation including experimental data are presented for eventual elimination of the digital computer. → over page

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ABSTRACT

Implementation of the Taylor Series Video Image Processing (TSVIP) algorithm for tracking and guidance is presented using an HP 2100 digital computer to solve the equation. Closed loop system operation was achieved using a Reticon 100 x 100 matrix photodiode camera, a microprocessor controlled A/D converter as an interface to supply signals to the computer and pan tilt servoes operating from computer generated signals to control camera position. Tentative studies of CCD implementation including experimental data are presented for eventual elimination of the digital computer. Alternate algorithm studies compare the capabilities of complementing and supplementing methods to the TSVIP. A hierarchy of algorithms is anticipated for eventual practical implementation.

Chapter I

INTRODUCTION

1.1 Background

This report describes the second year of research concerning the fundamentals of tracking and guidance using computer vision with an emphasis on Charge Coupled Device (CCD) discrete analog signal processing to achieve real time operation with small rugged and portable hardware. This choice of signal processing technology provides the possibility of having the image sensor and processing circuitry on the same substrate, thereby minimizing the interfacing problems between two major sections of the system. The discrete analog nature of the circuitry further eliminates A/D and D/A hardware. Refer to final report number ONR-CR233-092-1 for a complete description of research results for the first year.

Basically, the idea of the system is to compare successive frames of computer vision data to compute relative motion and displacements in three dimensions. This information is then used to derive guidance and/or pointing signals to keep the desired target in the center of the field of view. A major concern of the research has been the problem of processing rapidly the very large quantities of data required for effective real time computer vision tracking. See Chapter II and last year's report for a complete description of the system and its mathematical representation.

The Taylor Series Video Image Processing (TSVIP) algorithm was developed because an adequate algorithm could not be found in the literature that appeared to be CCD implementable. The basic tracking algorithm should be very fast, but it need not necessarily contain pattern recognition ability, registration ability, edging ability, etc. All these auxiliary operations can be obtained at a relatively slow rate if the tracking algorithm can keep the system functioning while they are given time to function. And, they probably will eventually be required because target discrimination with a very high level of confidence is a major goal.

The TSVIP operates on the gradient of the reflected target light intensity, i.e., the texture. If the texture function at a point on the target is described using a Taylor series and then truncated, a numerical method is available (called the Euler method) for extrapolating texture values. However, if the formula is solved for displacement of the target from the reference point, then texture measurements from successive frames of data yield calculated values of translation. If multiple points are measured and the problem formulated to include the affine transformation, dilation and rotation can be estimated as well as translation in two dimensions. The complete formulation is described in the previous report.

The major emphasis this year has been on implementation to validate system concepts and signal processing technology. Since CCDs are specialized devices, only a limited amount of experimental circuit work has been possible, but this was known beforehand to be the case. However, this work has presented many insights and given credance to the theoretical implementation work. An HP 2100 digital computer with associated components was used for the exerpimental system and is described in Chapter II. The CCD implementation work is described in Chapter III.

Only one method was considered during the first year for the required pseudoinverse described in Chapter II. Iterative methods are reported in Chapter IV for solving the estimation equations, i.e., obtaining pseudoinverse results. Chapter V contains advanced algorithm work in which the TSVIP and other algorithms are compared. Conclusions are written into each section because of the diverse nature of the individual parts. Chapter VI is concerned with recommended future work.

Three papers have been written on the results to date:

1. "Algorithm Development for Real-Time Automatic Video Tracking Systems " COMPSAC Proceedings (November 1979) (invited paper).

2. "A Model and Tracking Algorithm for a Class of Video Targets," accepted by <u>IEEE Translations on Pattern Analysis and Machine Intelligence</u> (1980).

3. "CCD Implementation of a Novel Video-Tracking Algorithm," accepted by <u>IEEE Transactions on Pattern Analysis and Machine Intelligence</u> (1980).

It is anticipated that at least three more papers will be published on the recent results of the research.

The second year goal of implementing closed loop equations was achieved.

CHAPTER II

EXPERIMENTAL SYSTEM

2.1 System Description

As already noted an experimental system was constructed to test operation of the TSVIP algorithm and in general lend credance to the theoretical work being done. A block diagram of the system is shown in Fig. 2.1. A Reticon MC/RS 520 camera [1] system acquires data from the target in the form of variation in light intensity or texture and outputs a video signal to an interface. The interface converts this information into a digital signal and latches it into the computer. The computer simulates the CCD portion of the TSVIP algorithm. It outputs signals to control a pan tilt mount in two dimensions although operation in only one dimension was performed. This pan tilt mount responds to the positional control signals to keep the target centered in the camera field of view.

Developing such an experimental system is a major undertaking even though a digital computer is used to simulate part of the hardware. Closed loop operation in two dimensions was achieved. Slow delivery of parts and typical hardware problems such as noise and faulty components were encountered as one normally expects.

2.2 Hardware Drivers

A device driver is the software necessary to interface the computer with the actual hardware. It provides the overall system control and the communication between the hardware and the computer. All the software drivers were written in HP assembler language in

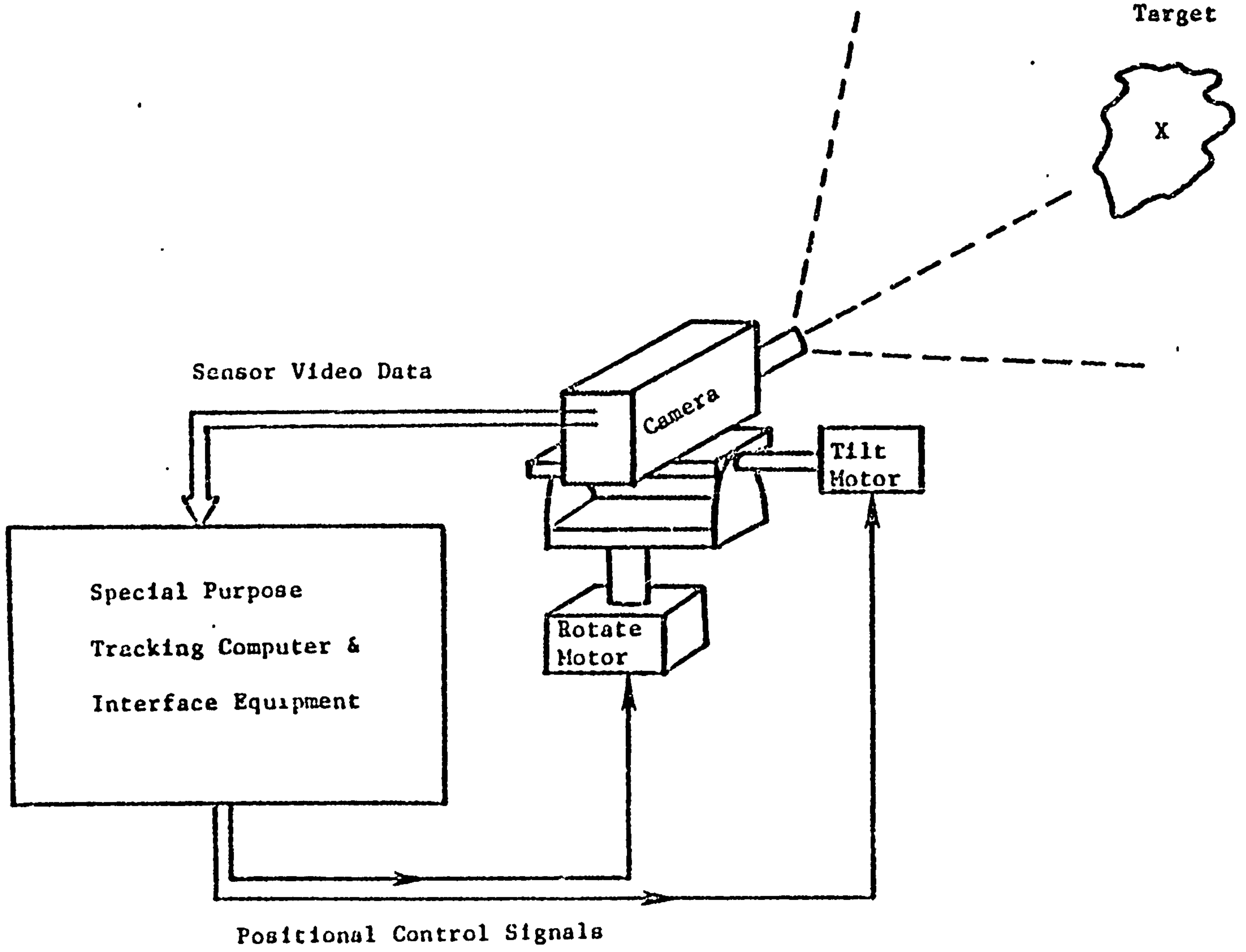

Target
X
Sensor Video Data
Camera
Tilt Motor
Rotate Motor
Special Purpose Tracking Computer & Interface Equipment
Positional Control Signals

Figure 2.1 Video Trackins System Example

order to be compatible with the existing system.

In order to understand the operation of the device drivers, it is necessary to present a brief description of the facilities. The tracking simulation and emulation has been done in the Control and Computer Systems Laboratory. Major items of equipment used are:

1) HP 2100A mini computer
2) HP magnetic tape drive
3) HP disc drive
4) Reticon TV camera
5) HP X-Y display
6) Tektronix graphics terminal
7) GE Terminet
8) High speed tape punch and optical tape reader
9) Pan tilt mount
10) Computer controlled motorized arm

The HP 2100 has a core memory size of 32K and can run under Disc Operating System (DOS) or Binary Control System (BCS), the former residing on the disc and the latter, loaded directly into core memory [2]. Since most developmental programs were written in Fortran (with the exception of the drivers), and because DOS allows relatively easy, fast editing, compilation, loading, and execution of routines in both Fortran and HP Assembler, DOS was used exclusively.

Rectangular pulses are generated and sent to the drivers by the HP 2100A through an I/O channel. The HP 2100A is a mini computer featuring a relatively strong instruction set, plug in interfaces and modular software. Standard features include memory parity generation and checking, memory and I/O protect for executive systems, extended arithmetic capability,and power fail interrupt with automatic restart. It has a 16 bit word length, 980 nanosecond cycle time, and 80 basic instructions.

Interfacing of peripheral devices is accomplished by plug-in interface cards (see Fig. 2.2). The computer mainframe can accommodate up to 14 interface cards and up to 45 with the I/O extender added. All I/O channels are buffered and bidirectional, and are serviced through a multilevel priority interrupt structure.

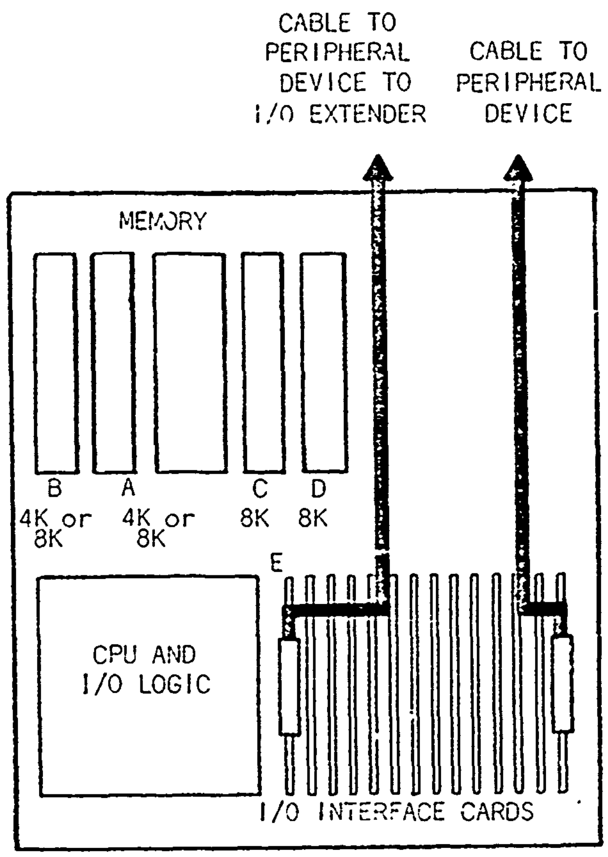
The 17 I/O instructions provide the capability to set or clear the I/O flag bits, and to transfer data between an I/O channel and the A or B registers. The general purpose of the I/O system is to transer data between the computer and external devices. Normally data is transferred through the A or B registers. This type of transfer occurs in three distinct steps:

1) between external device and its interface card in the computer
2) between the interface card and the A or B registers
3) between the A or B registers and memory.

This three step process applies to data following both in and out of the memory. The basic block diagram is shown in Fig. 2.3.

Hardware controllers are connected through buffers by a cable directly to an interface card inside the computer. The interface card in turn plugs into one of the 14 I/O slots. Each slot is assigned a fixed address, called a select code. The computer can then communicate with the device on the basis of its select code (see Fig. 2.1).

For this system, interface cards were installed in the slots



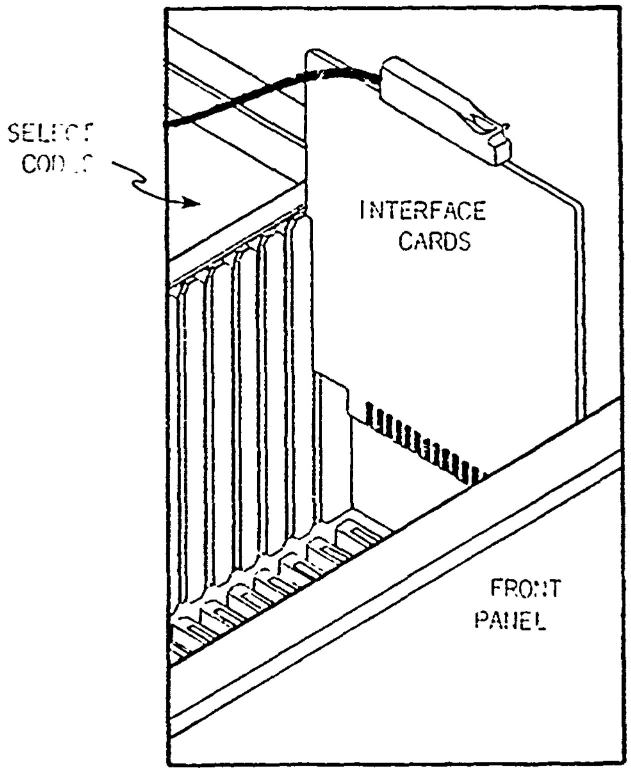


Figure 2.2 I/O Interface to HP 2100

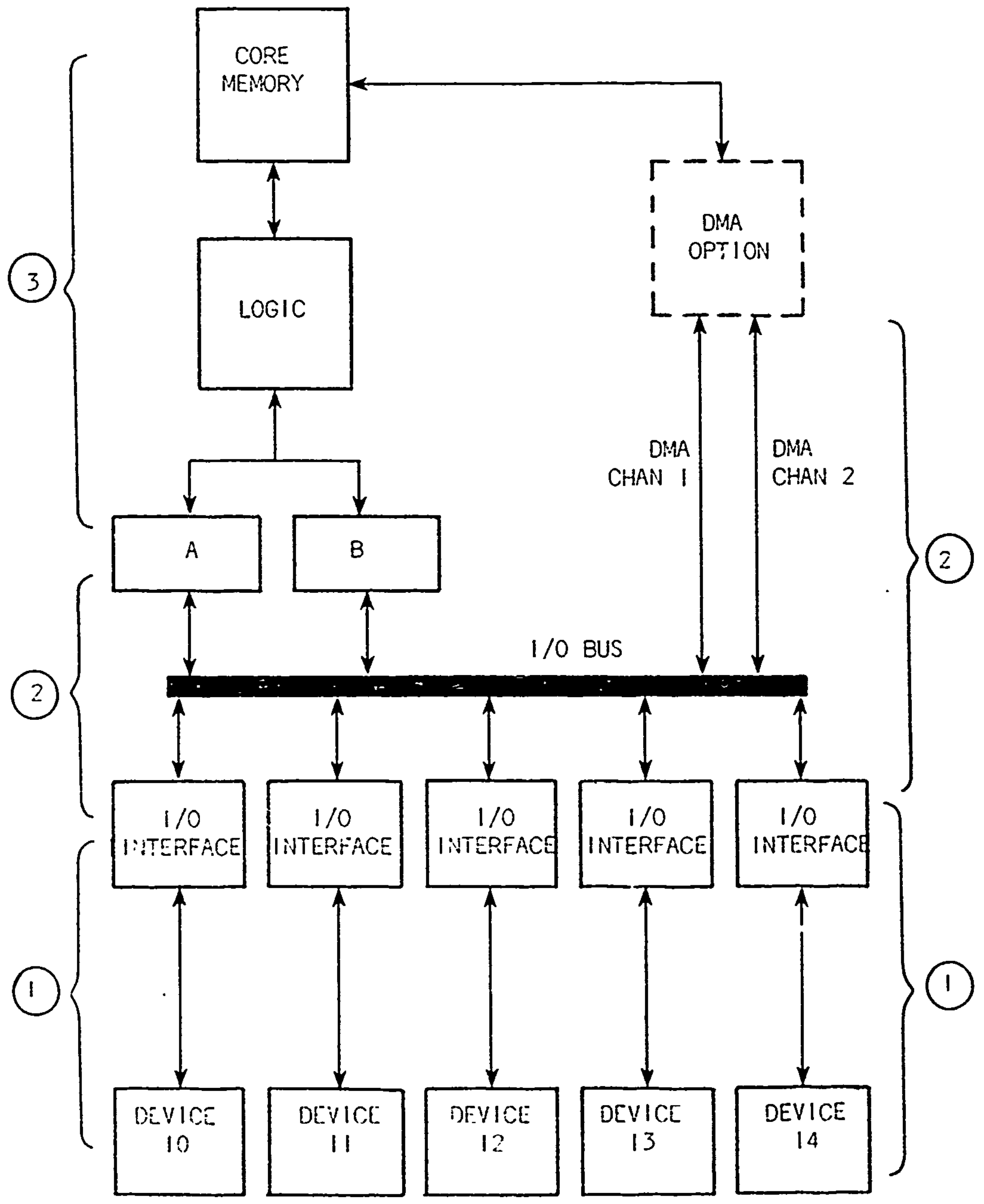


Figure 2.3 Block Diagram of HP 2100 I/O Interface

corresponding to select codes 16 and 36. Data to be transferred are loaded into the register and are a suitable form for output. The operation begins with a HP assembly language program instruction to transfer the data from the A register to the interface buffer. The buffer is a flip-flop register for the intermediate storage of data and its data capacity is 16 bits. Since this is a non-interrupt transfer, and control and flag flip-flops are not used, the sixteen bits of binary data are immediately transferred to the external devices, where a binary zero corresponds to zero volts and a binary one corresponds to five volts. Pin connections for these interface cards are shown in Appendix 2.1.

2.2.1 Pan Tilt Driver

A binary one can be stored in any one of bits twelve to fifteen (depending on the desired movement of the pan and tilt motors), causing that bit to be high and output five volts to the corresponding input terminal of the driver hardware [3,4]. Five different control words are output periodically, one at a time, depending on which motor is to be operated and in which direction it is to be moved. Figure 2.4 lists the code used for the control words. Rectangular pulses are sent to the desired input of the driver by outputting one of these four control words or 0 periodically in order that the desired motor move the required number of steps.

The assembler subroutine is called by this FORTRAN subroutine call:

```
CALL MOTOR(ISTEP1,ISTEP2,IDIR,IPER)
```

where

Code Used for the Data

Data (Octal)	Bit #
10000	Bit 12 is high
20000	Bit 13 is high
40000	Bit 14 is high
100000	Bit 15 is high
0	All bits are low

Bits Used to Output the Data

Bit #	Motor Driver 1	Motor Driver 2
12	Forward	—
13	Reverse	—
14	—	Forward
15	—	Reverse

Figure 2.4 Pan Tilt Mount Hardware Control Codes

ISTEP1	is the number of steps to be taken by the tilt motor
ISTEP2	is the number of steps to be taken by the pan motor
IDIR	is the direction of rotation
0	for CCW tilt and CCW pan rotation
1	for CW tilt and CCW pan rotation
2	for CCW tilt and CW pan rotation
3	for CW tilt and CW pan rotation
IPER	is the speed of the motors
1	for 20 steps/second
2	for 100 steps/second
3	for 200 steps/second

A simple flow chart of the program is illustrated in Fig. 2.5. The actual assembler program is listed in Appendix 2.3.

2.2.2 Camera Driver

The driver for the camera controller utilizes non-interrupt data transfers and direct memory access, see Figs. 2.6 and 2.7 (several of the figures are similar to information from [2,3]). In a manner similar to the pan tilt mount, the computer outputs the control words to the camera controller by a non-interrupt data transfer; but, because the data rate of the camera output is faster than that of a non-interrupt transfer it was necessry to directly transfer the data into memory.

As already mentioned and as shown in Fig. 2.7, the purpose of the direct memory access (DMA) is to provide a direct data path which is software assignable between memory and the high speed peripheral

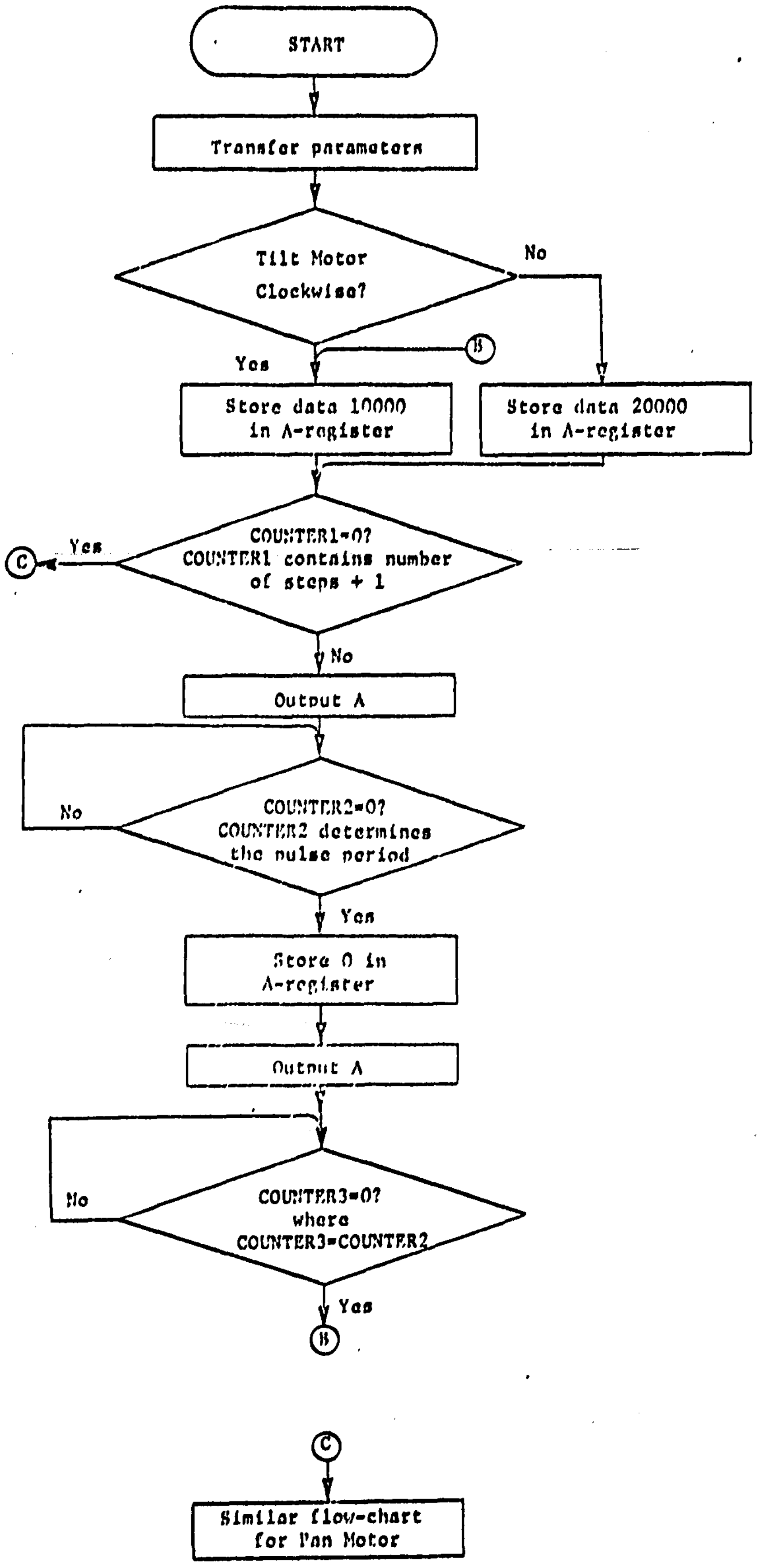
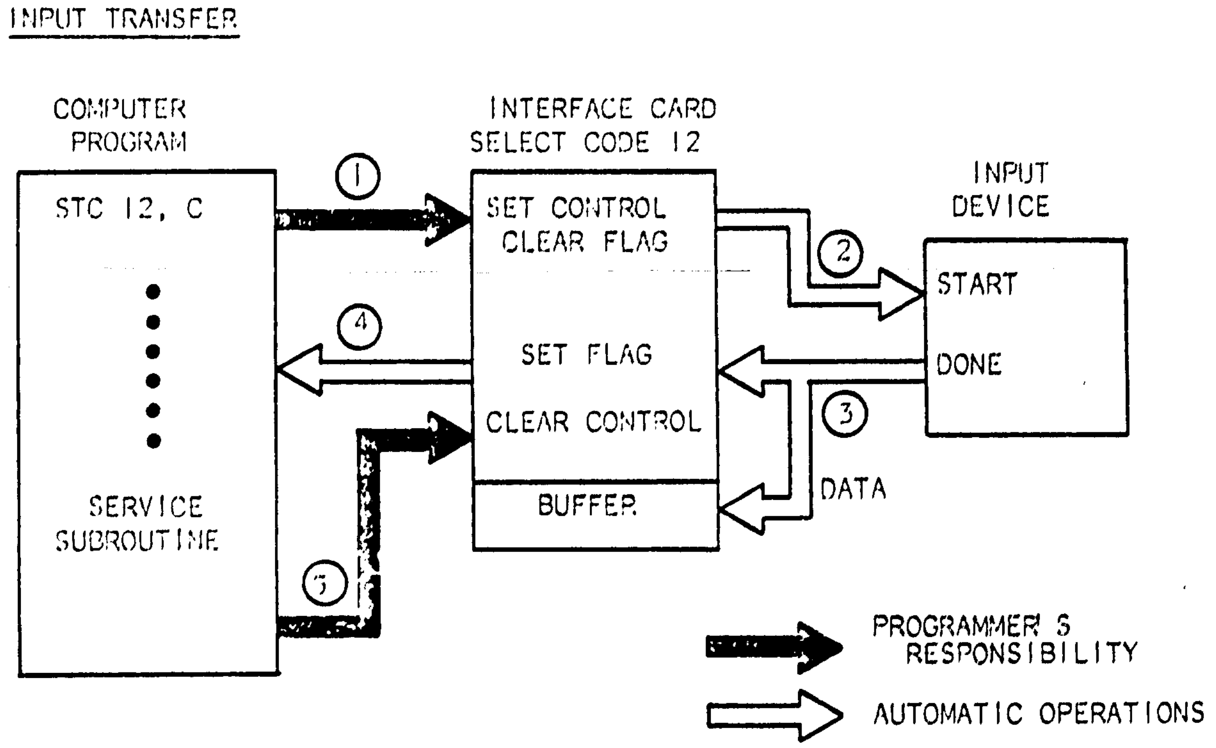

START
Transfer parameters
Tilt Motor Clockwise?
No
Yes
B
Store data 10000 in A-register
Store data 20000 in A-register
COUNTER1=0? COUNTER1 contains number of steps + 1
Yes
C
No
Output A
COUNTER2=0? COUNTER2 determines the pulse period
No
Yes
Store 0 in A-register
Output A
COUNTER3=0? where COUNTER3=COUNTER2
No
Yes
B
C
Similar flow-chart for Pan Motor

Figure 2.5 Flowchart of Pan Tilt Driver



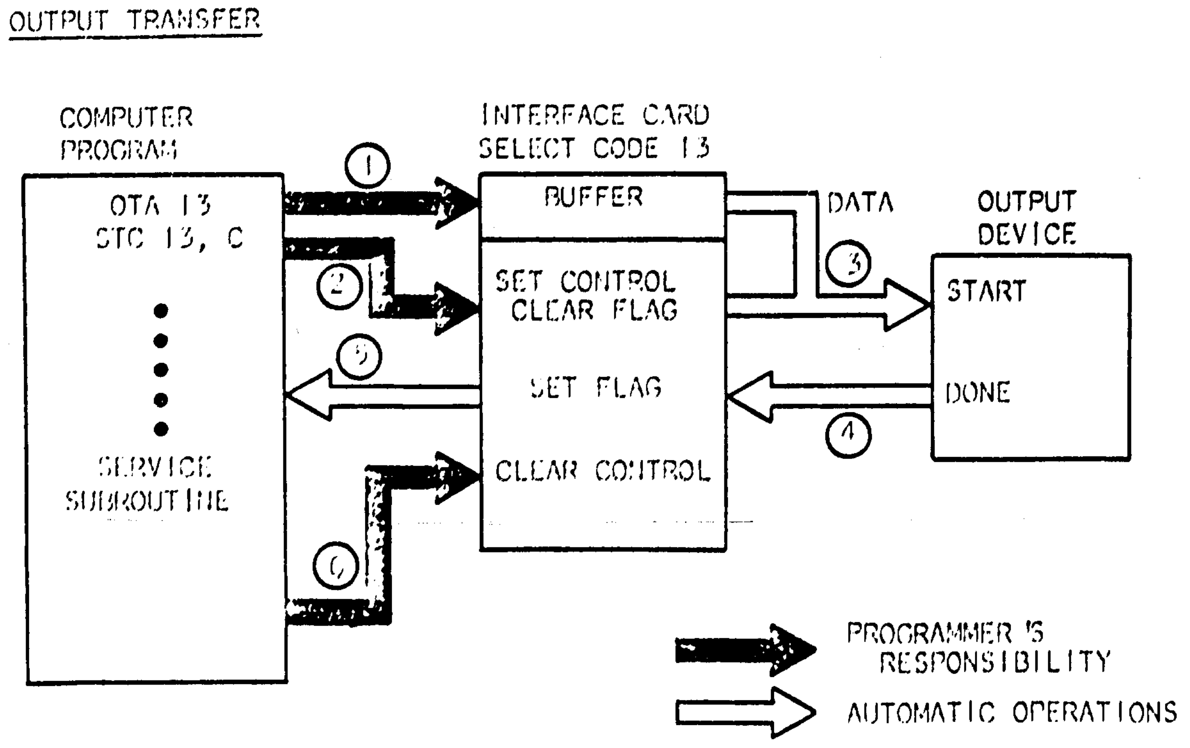
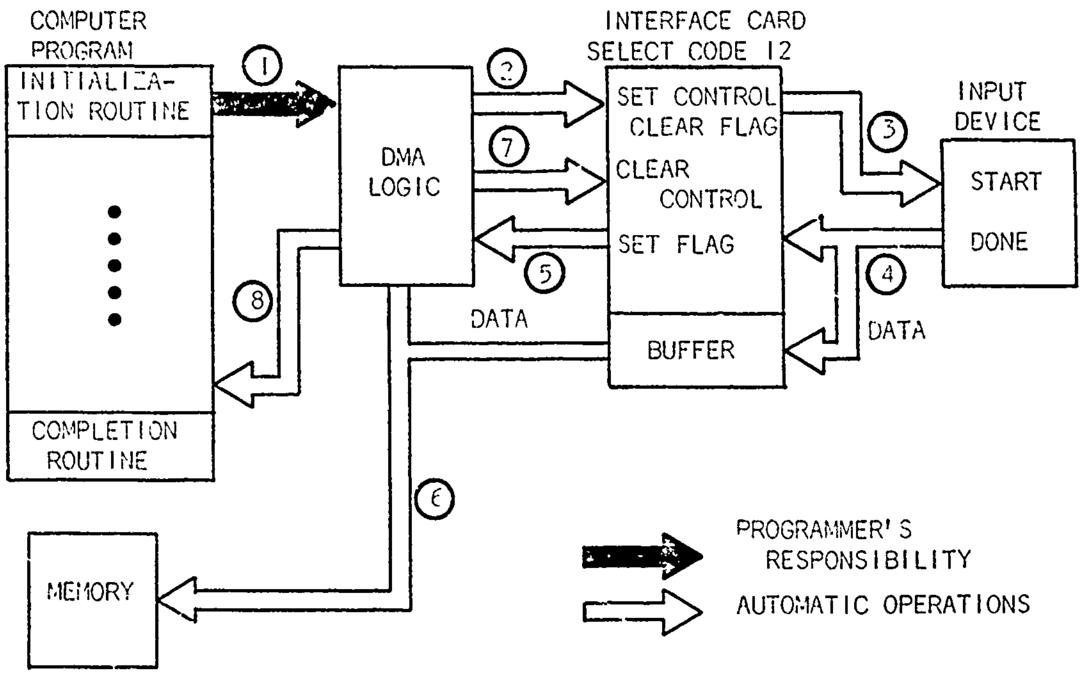


Figure 2.6 Block Diagram of HP 2100 Non-interrupt Data Transfers



Control Word 1 (Device Control)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	STC		CLC	(Not used)							Device Select Code					
0	$\overline{\text{STC}}$		$\overline{\text{CLC}}$													

Control Word 2 (Memory Control)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	IN	Memory Address														
0	OUT															

Control Word 3 (Block Length Control)

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Word Count															

Figure 2.7 Block Diagram of HP 2100 Direct Memory Access

device. DMA accomplishes this purpose by stealing a memory cycle instead of interrupting to a service routine. When DMA is accessing memory, it has priority over the central processor's access to memory. The DMA data rate at maximum is about 1 MHz (16 bit words) but in our case it was about 500 KHz.

The DMA transfer is initiated by an initialization routine and from then on operation is under the automatic control of the hardware. The initialization routine tells the DMA hardware which direction to transfer the data, where to put the data in memory, which I/O channel to use, and how much data to transfer. This information is given by three control words. These three words must be addressed specifically to the DMA card. Figure 2.7 shows the format of the three control words. Control Word 1 identifies the I/O channel to be used, and provides two options not used in our software (Option 1 is the STC and CLF to the I/O channel at the end of each DMA cycle and Option 2 is the CLC to the I/O channel at the end of a block transfer).

Control Word 2 gives the starting memory address for the block transfer and Bit 15 of this word determines whether data is to go into memory or out of memory. Control Word 3 is the 2's complement of the number of words to be transferred into or out of memory (i.e. length of the block). This number can be from -1 to -32768 although it is obviously limited by the size of the available memory.

For the non-interrupt portion of the data transfer, four control words are sent to the camera controller: XSTART, YSTART, XSTOP, and YSTOP. The first seven bits (0 - 6) of each word identify a starting or stopping address for the software selectable camera window. The seventh and eighth bits of each control word identifies the control word. The ninth bit of the last control word initiates the camera output.

In this manner, any portion of the camera picture (100x100) can be selected for processing. This became a necessity for the experimental system due to the limited memory available and processing speed. The software drivers for both of these processes can be found in Appendix 2.3.

2.3 Video Interface

A brief description of the camera is necessary before the interface can be discussed (2). The camera is a Reticon MC 520 photodiode camera. It provides a 100 x 100 pixel discrete analog picture. The output is pixel by pixel, row by row string of sampled-and-held pulses. Each pulse represents the grey level at a particular pixel in the image matrix. When the MC 520 is used in conjunction with its companion controller, the RS 520, (as it was in this case) various synchronizing signals are made available to the user. A pixel clock (GCLK) is synchronized with the beginning of each sampled-and-held pulse of video data and is blanked during all retrace intervals. The line enable (LEN) signal is valid during each row of 100 pixels and provides a means of knowing which row of the video data is being "clocked out" at any given time. The frame enable (FEN) signal is valid during each entire 100 x 100 pixel frame and invalid during the retrace interval between frames. It allows the user to easily synchronize his equipment with the start of any picture frame. These signals make the design of the video interface fairly straightforward.

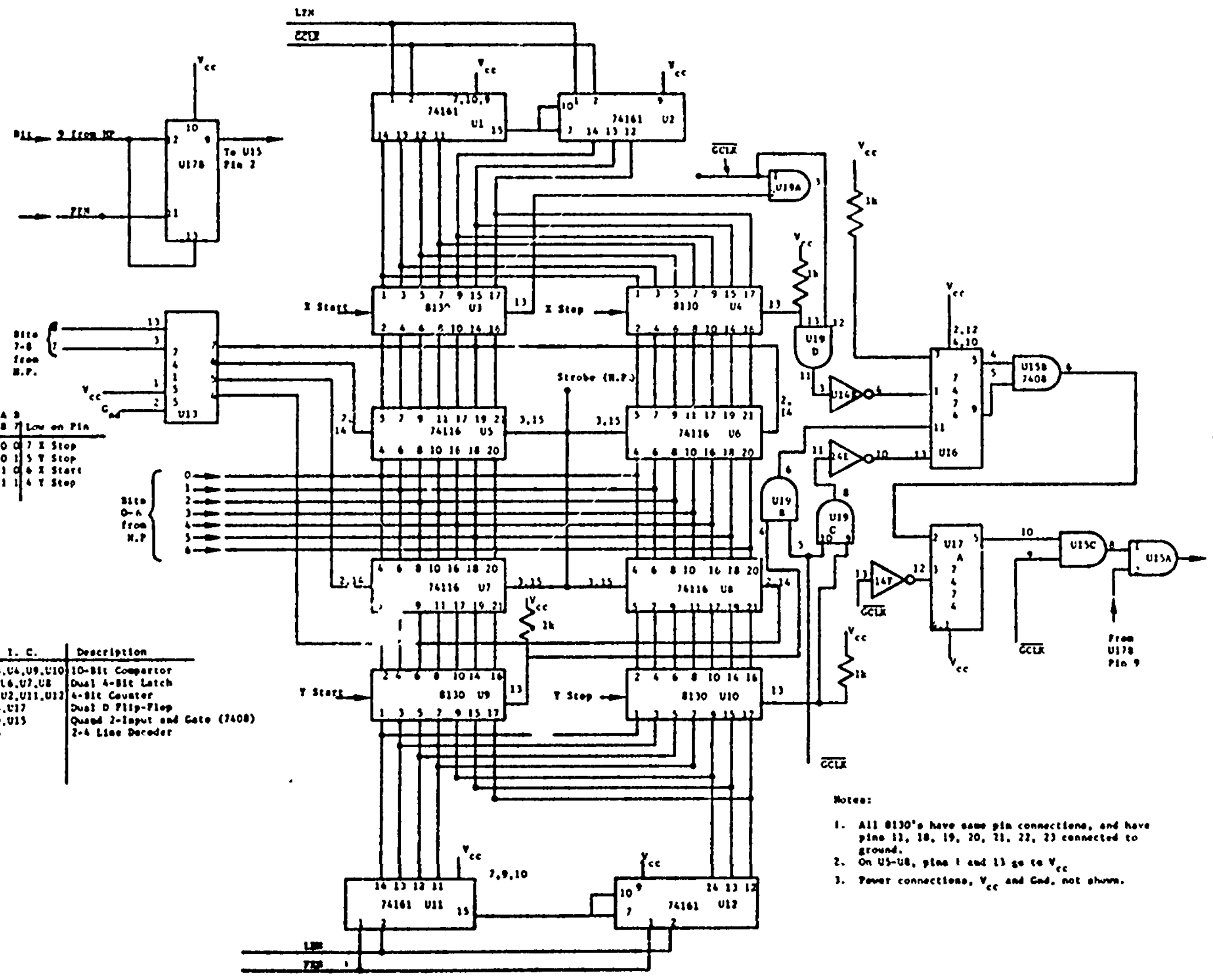
The interface had to meet certain requirements. First, and foremost, it had to provide some form of data reduction. Each 100 x 100 pixel image required 10,000 words of computer storage. If it were necessary that two successive image frames be stored in memory simultaneously then there would be little memory available for programs. Thus, some form of data reduction was imperative. Since the tracking algorithm utilized only those image points within the target, a means of selecting out only those particular pixels for transmission was needed. The technique employed will be described in the general description of the interface. The interface was also required to digitize the discrete analog image into a sufficient number of grey levels at speeds approaching one megahertz, the D.M.A. rate of the HP 2100.

Finally the interface was required to allow the camera to clock out image frames continuously. This was required to prevent saturation of the photodiode array. The camera operates by integrating the light incident on each photodiode for the entire period between which each photodiode is sampled. Thus allowing the camera to "sit" and only clock out frames on demand would allow it to integrate light for too long a period of time between samplings. This would result in the saturation of the photodiode array. To avoid this saturation the camera was allowed to run freely, clocking out frames continuously. When the computer signals the interface to ask for the next image frame, the interface must be able to find the beginning of the next available image frame and begin data transmission with the first pixel in the frame. The means by which this requirement and all the other requirements were satisified will become clear as the interface is described.

The camera-computer interface consists of two major subsystems. The digital subsystem allows the user to select a desired portion of an image for transmission to the computer. The analog subsystem performs the analog to digital conversions necessary for communication with a digital computer. The entire interface resides on one 4.5 by 9 inch wire wrap circuit card. It is installed in the RS 520 controller which has extra slots in its card cage meant specifically for user hardware such as the interface.

The digital subsystem allows the user to select from software a rectangular (or square) "window" or subsection of the entire image for transmission to the computer. The user specifies the parameters of the desired window by transmitting, to the interface, four control codes specified in software. A frame is acquired by sending "go" command which is usually issued with the last control code.

The operation of the digital subsystem is best understood by separating its operation into an initialization mode and a run mode. Figures 2.8, 2.9, and 2.10 should be referred to throughout this description. The initialization mode allows the user to program the interface which specifies the software selectable window. Bits seven and eight of the 16 bit computer word are used to select which of four eight bit (only seven bits used) latches is to be initialized. Bits zero to six of each word are then used to initialize each of the four latches. Each latch contains the coordinates within the 100



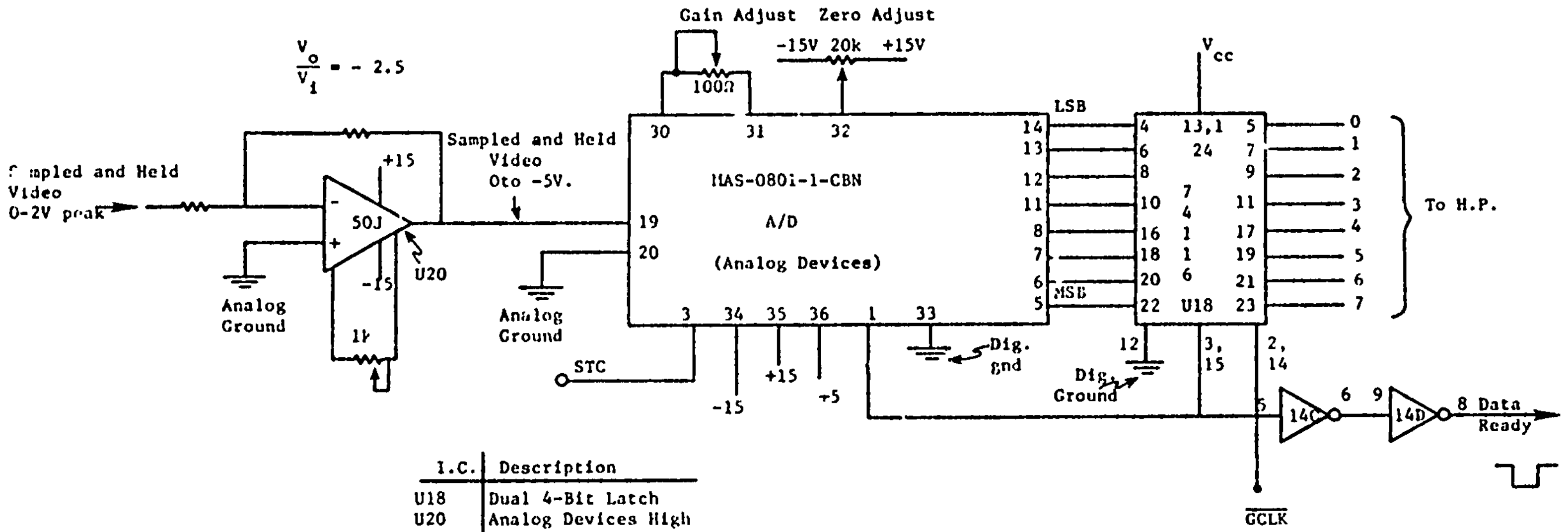
A B Bits 8 7	Low on Pin
0 0	7 X Stop
0 1	5 Y Stop
1 0	6 X Start
1 1	4 Y Stop

I. C.	Description
U13,U4,U9,U10	10-Bit Comparator
U5,U6,U7,U8	Dual 4-Bit Latch
U1,U2,U11,U12	4-Bit Counter
U16,U17	Dual D Flip-Flop
U19,U15	Quad 2-Input and Gate (7408)
U13	2-4 Line Decoder

Notes:

1. All 8130's have same pin connections, and have pins 11, 18, 19, 20, 21, 22, 23 connected to ground.
2. On U5-U8, pins 1 and 13 go to V_{cc}
3. Power connections, V_{cc} and Gnd, not shown.

Figure 2.8 Digital Subsection of Video Interface



I.C.	Description
U18	Dual 4-Bit Latch
U20	Analog Devices High Performance Op-Amp

Figure 2.9 Analog Subsection of Video Interface

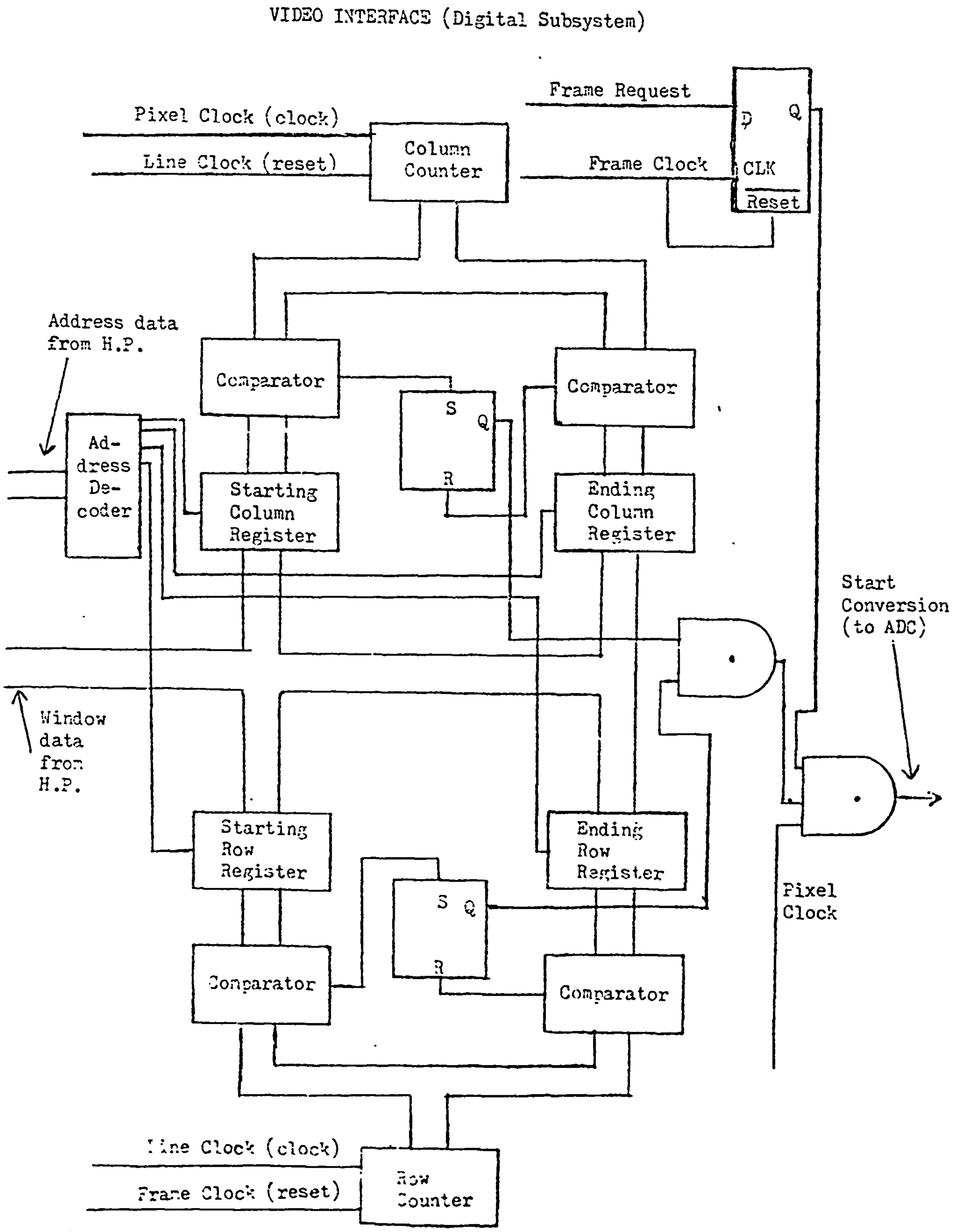


Figure 2.10 Block Diagram of Digital Subsection of Video Interface

x 100 pixel array of the start or stop postion of the column or row desired. The four codes are referred to as XSTART, XSTOP, YSTART, and YSTOP and indicate the starting column, ending column, starting row, and ending row, respectively of the desired window. Figures 2.8 and 2.10 provide an illustration of this.

The term "run mode" is actually a slight misnomer since the digital subsystem is actually free running while its output is disabled until a "go" command is issued. The four 4 bit counters (U1, U2, U11, and U12) are used in pairs to form two 8 bit counters in order to keep track of the pixel whose value is being clocked out. The "X-counter" is clocked by the logical complement of GCLK, the pixel clock, which occurs as each successive pixel clocked out. It is reset by the LEN signal. Thus the value of the X-counter at any given time is the column coordinate of the pixel being clocked out at that time. The "Y-counter", which is clocked by the LEN signal and reset by the the FEN signal, keeps track in a similar fashion of the row coordinate of the pixel being clocked out. Thus the values of the X and Y counters taken together provide the coordinates of the pixel being clocked out at any given time.

Digital comparators (U3, U4, U9, and U10) are used to compare the location of the pixel being clocked out at a particular time to the location of the window limits as stored in the four latches during initialization. The output of the comparators provides the information necessary to know whether the pixel being clocked out is within the specified window. The XSTART and XSTOP comparators set and reset, respectively a flip-flop (U16A) whose output status tells whether the column coordinate of the pixel being clocked out is within the specified window. The YSTART and YSTOP comparators provide the same information about the row coordinate by setting and resetting another similar flip-flop (U16B). Thus, by combining the outputs of the two flip-flops using a logical AND function provides a single digital signal whose status tells whether the pixel being clocked out is within the desired window. The window status signal combined with information as to whether a frame request has been made is used to appropriately enable or disable the clock to the analog subsystem.

The user makes a request to acquire a frame by setting bit nine of the last control word. This bit is clocked into a D-type flip-flop (U17B) by the FEN signal. This causes the output of the flip-flop to be synchronized with the start of the next available frame. The output of this flip-flop combined by a logical AND function (U15) with the window status signal is used to enable the clock to the analog subsystem.

The main task of the analog subsystem is to perform analog-to-digital conversion. This subsystem consists of high performance operational amplifier, and eight bit one megahertz analog-to-digital converter, and an eight bit latch. A schematic diagram is shown in Figure 2.9. The operational amplifier gain of -2.5 serves to scale the 2 volt maximum sampled-and-held video from the camera to a 0 to -5 volt range so as to make use of the entire dynamic range of the ADC. The ADC is capable of performing conversions at speeds up to one megahertz. The actual clock rate is set by adjusting the internal clock of the RS 520 camera controller. The latch connected to the ADC output holds each conversion result for an entire conversion period to allow sufficient time for the computer to read each piece of data. The start-conversion (STC) signal to the ADC is the output of the digital subsystem. Thus, the ADC only receives STC signals when a frame has been requested by the user and the pixel being clocked out is within the user specified window.

The operational details of the control codes required to initialize the interface are as follows:

CODE	BIT	9	8	7	6	5	4	3	2	1	0
XSTART		0	1	0	X	X	X	X	X	X	X
XSTOP		0	0	0	X	X	X	X	X	X	X
YSTART		0	0	1	X	X	X	X	X	X	X
YSTOP		0	1	1	X	X	X	X	X	X	X
YSTOP with "go"		1	1	1	X	X	X	X	X	X	X

where X is user specified.

One important point to note is that after a frame request is made by sending the last control code with bit 9 set, this bit must be reset and then set again when a frame is next requested. Failure to reset bit 9 of the latched output port between frame requests will render the frame synchronizing apparatus ineffective.

The interface is an open loop device. This means that it provides no handshaking lines (other than the usual strobe or flag) either when latching control codes or transmitting data to the computer. To assure consistent operation, the system clock (internal to RS 250) must be set at less than 800 KHz. In this way the D.M.A. rate of the HP 2100 is not exceeded and the propagation delay inherent in latching the output of the ADC is taken into account.

2.4 Tracking

The purpose of this section of the system is to estimate the affine parameters using the TSVIP algorithm.[5]. A brief development of the algorithm is given below (see ONR-CR-233-092-1 for complete details):

$$\underset{\sim}{d} = D_c \underset{\sim}{a} \tag{2.1}$$

where

$\underset{\sim}{d}$ is the N x 1 scene difference vector

$\underset{\sim}{a}$ is the 4 x 1 total affine parameter vector

D_c is the constrained N x 4 matrix

D_c is

$$D_c = [P_c : G] \tag{2.2}$$

where

P_c is the N x 2 matrix of weighted spatial derivatives

G is the N x 2 matrix of spatial derivatives

$$D_c^+ = [P_c : G]^+ = \begin{bmatrix} P_c^+ - P_c^+ G C^+ \\ C^+ \end{bmatrix} \tag{2.3}$$

where

$$C^+ = [I - P_c P_c^+] G \tag{2.4}$$

The affine vector can be estimated by

$$\hat{\underset{\sim}{a}} = \begin{bmatrix} \hat{\underset{\sim}{a}}_c \\ \hat{\underset{\sim}{b}}_c \end{bmatrix} \tag{2.5}$$

where

$$\hat{\underset{\sim}{a}}_c = (P_c^+ - P_c^+ G C^+) \underset{\sim}{d} \tag{2.6}$$

$$\hat{\underset{\sim}{b}}_c = C^+ \underset{\sim}{d}$$

Software was developed to implement this algorithm with two intentions in mind: first, ease of implementation; and second, ease of modification. Therefore the software took the form of one overall control algorithm and many array processing subroutines. The software is well documented and fairly straightforward following the development found on the previous page. The software can be found in Appendix 2.3.

2.5 Open Loop Tracking

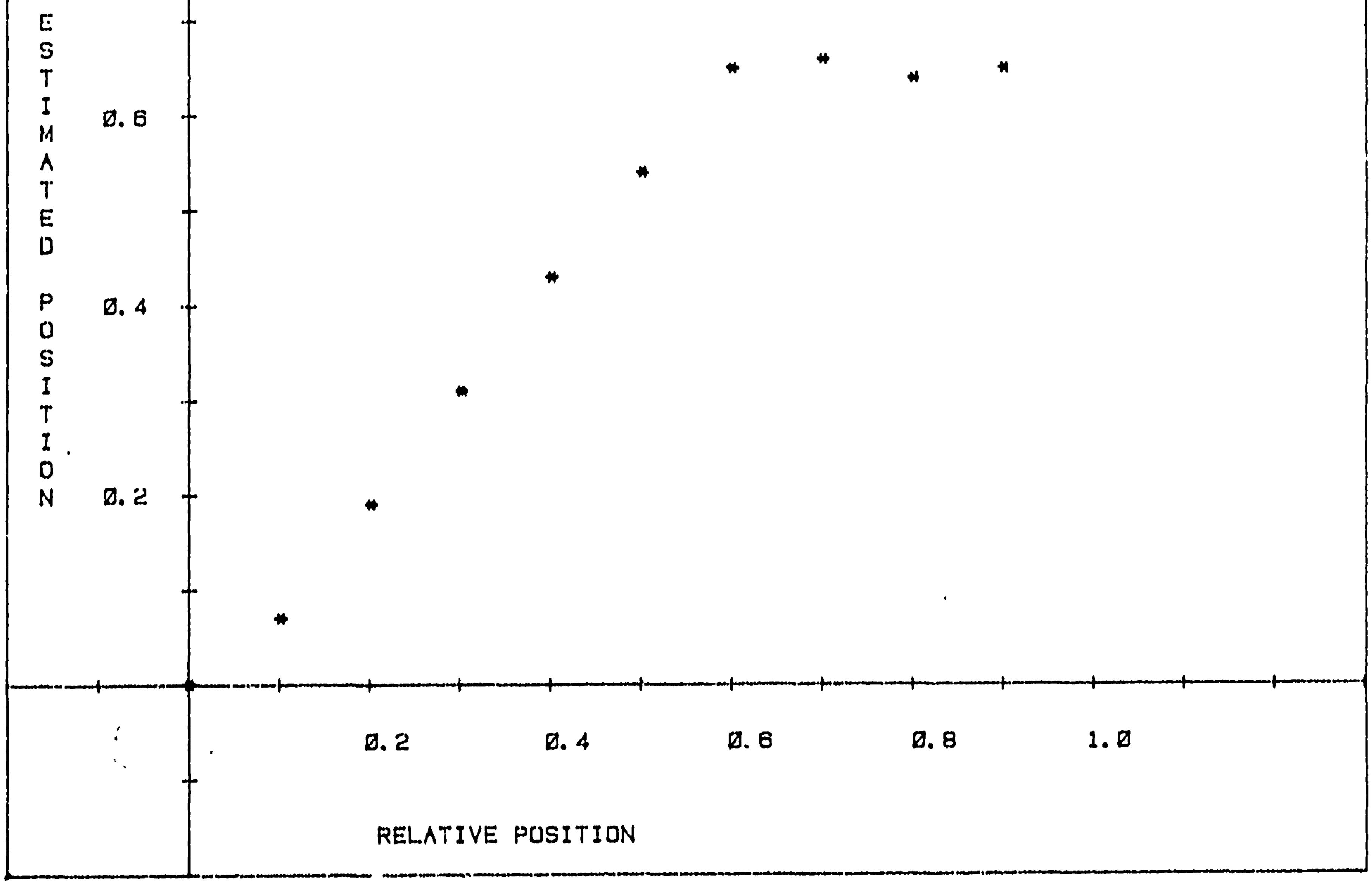
Upon completion and testing of the software and hardware, the relationship between relative position and estimated position was examined. Figures 2.11, 2.12, and 2.13 demonstrate the sensitivity of the experimental system to noise. A great deal of noise smoothing had to be incorporated into the tracking system in order to compensate for the slow sampling rate (once every 30 seconds) and a very noisy lighting environment. With a greater processing speed (such as CCD technology is now capable of), a faster sampling rate can be achieved which theoretically should decrease the magnitude of changes in the target's lighting environment.

After the effect of noise has been reduced, Figure 2.13 shows that the TSVIP algorithm does generate linear position estimates for small target movements from the origin. With a fast enough system sampling rate, all target movements can be limited to this range.

2.6 Closed Loop Tracking

Once the TSVIP algorithm produces positional estimates, it is necessary to translate then into pan tilt control signals. Since a priori knowledge of the target size and distance to the sensor is

Figure 2.11 -- Open Loop Data (each point averaged ten times).



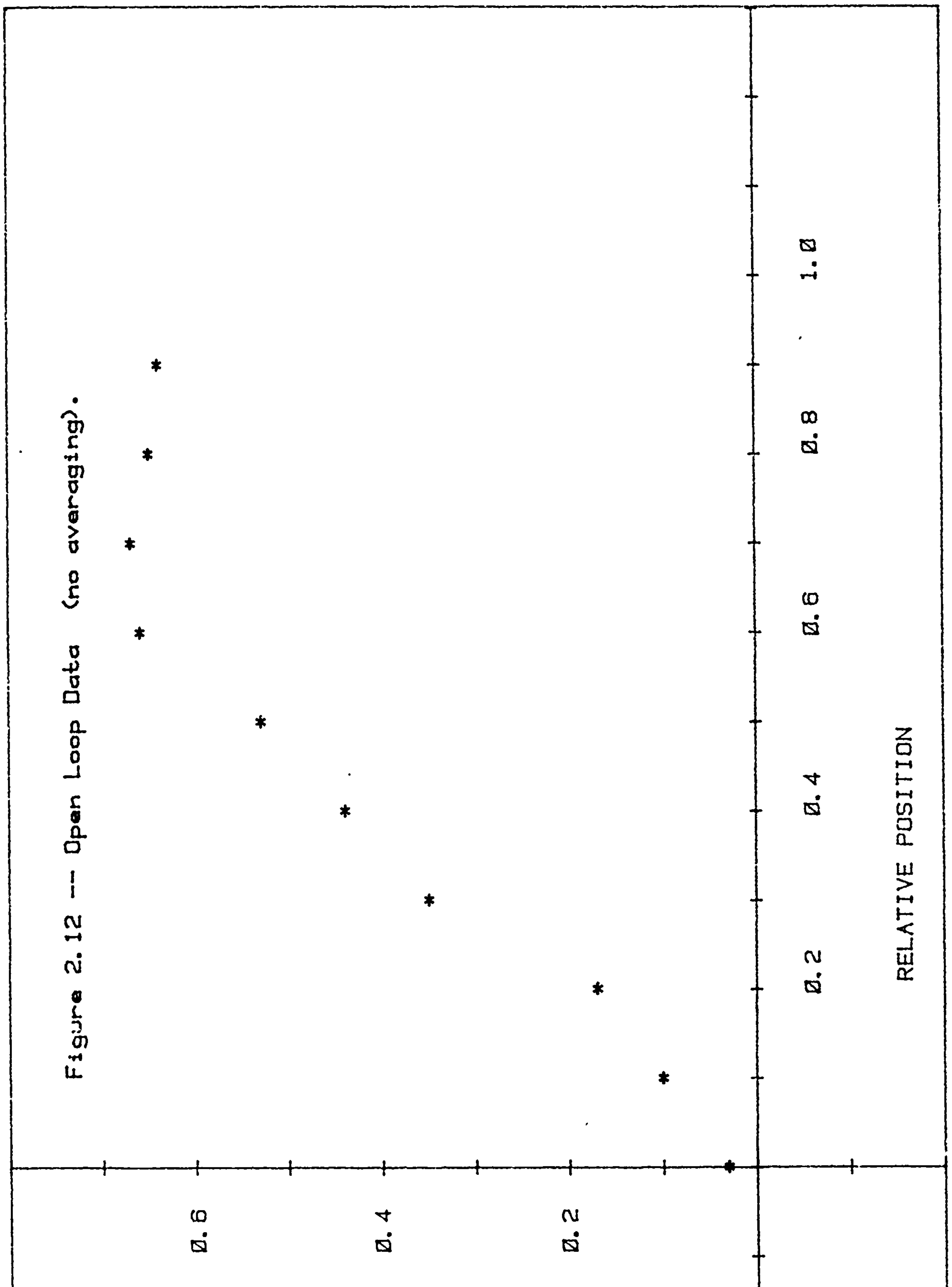
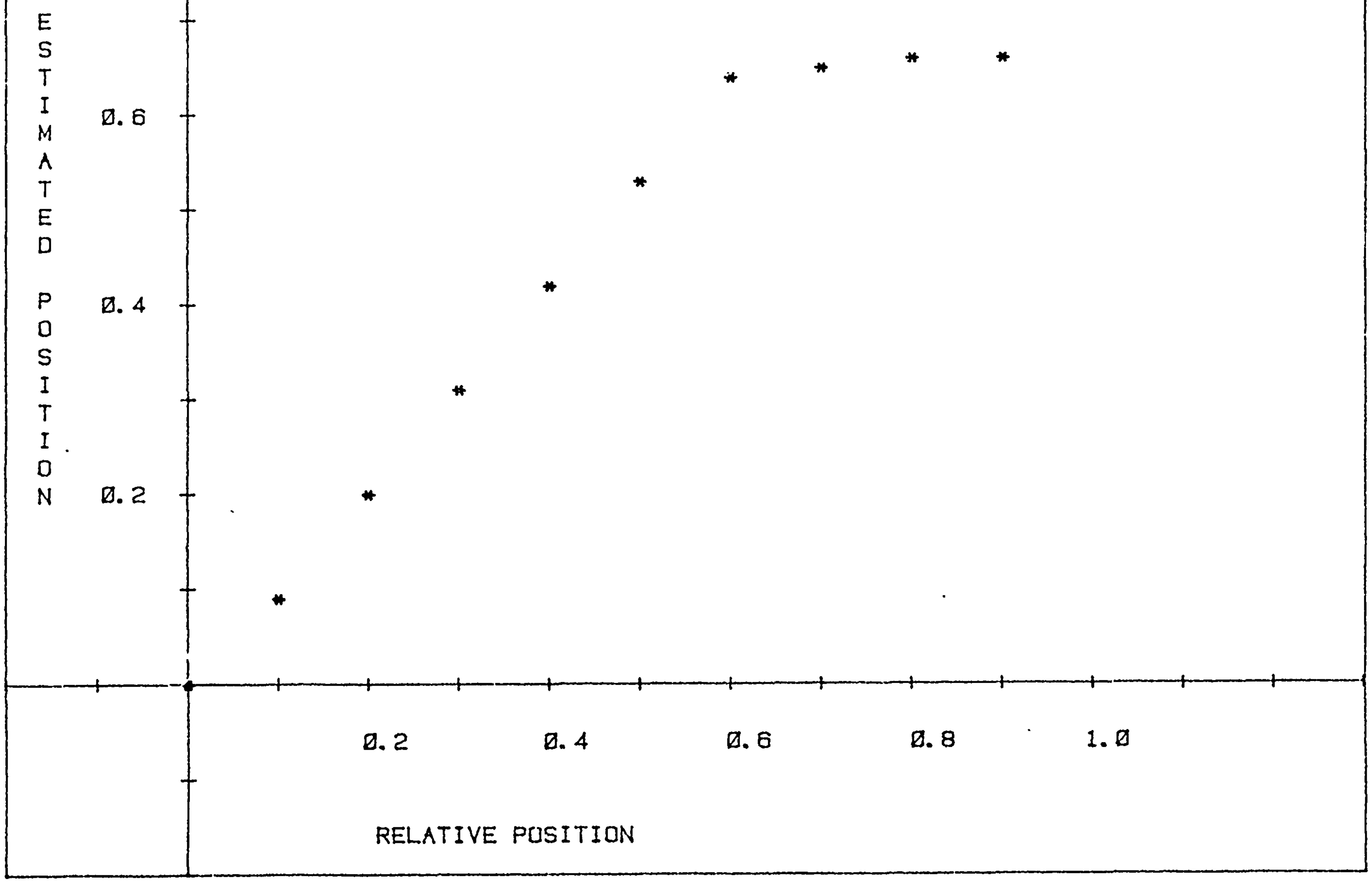


Figure 2.12 -- Open Loop Data (no averaging).

Fiqure 2.13 -- Open Loop Data (each point averaged 100 times).



not available, an alternate method is needed. A straightforward method is to move the camera in the direction followed by the target with a constant step size until the error is within certain limits. This method generally guaranteed convergence at the expense of processing time.

A second approach has been tested where the values for guidance control signals were found by interpolating between the previous and present postion estimates and the previous control signal. This algorithm was much faster than the previous one but was very sensitive to noisy position estimates as long as the target was in the linear region of the TSVIP algorithm. Outside of this region, the response time of this algorithm was decreased although it was still better than that of the first method. This deficiency could be avoided provided that the system sampling rate was fast enough to limit target motion to this range.

A real environment tracking sequence of scenes copied from the graphics display can be found in Appendix 2.4. The initial scene shows the position of the target after it has moved away from the origin. The remaining images display the target position after computer simulating the TSVIP algorithm attempts to center the target in its coordinate system. Note that the sequence ends when the computer has successfully tracked the target back to its origin.

Closing the feedback loop allows any errors generated from the previous position estimates or camera position control signals to be corrected as can be seen in Appendix 2.4. It took eight iterations for our tracking system to track the target back to its origin but with an increase in processor speed as with CCD technology real time video tracking becomes a reality. Since it is impossible to increase the computation speed of the HP 2100, it was necessary to slow down the target motion. Moving at a speed which kept the target in the field of view of the camera, any single target which could be segmented from the background was capable of being tracked for any length of time as long as the above conditions were met.

CHAPTER III

CCD IMPLEMENTATION

3.1 Introduction

Algorithms such as the TSVIP require the manipulation of matrices with variable elements. Matrix multiplication is the most commonly performed operation, but in some cases matrix inversion is also necessary. The TSVIP algorithm (in reduced form) requires the inversion of a 2x2 matrix with variable elements. This inversion can be performed using only one analog divider (in addition to CCD registers and analog multipliers). The block diagram and schematic diagrams for the implementation of the complete TSVIP were presented in the final report for the period August 1978 - August 1979 (Report ONR-CR233-092-1). The processor requires 16 subsystems, all of which, except the spatial derivative estimator use CCD devices. Some require analog multipliers also, and only one, as mentioned above, an analog divider. It is suggested in [6] that the use of analog dividers can be avoided in matrix inversion if the method of inversion by products is used. However this still requires the use of analog multipliers plus n digital divisions for the inversion of an n x n matrix. For a 2 x 2 matrix it seems that the disadvantages of this method outweigh the possible advantages, and the use of a single analog divider is adequate.

Several methods for the implementation of programmable filters which can be extended to matrix operations have been reported in the literature. The most promising one, [7], uses a combination of CCDs and digital shift registers for the multiplication of a variable vector by a matrix with elements known a priori. More details on this approach will be given in Sect. 3.3. The method could be used also for a variable matrix, but the speed of operation would then be slowed down by the loading time of the shift register, plus the A/D conversion time. Except for this possibility, no other method for variable matrix operations has been reported, to our knowledge, which avoids the use of analog multipliers.

3.2 Sum of Products (SOP) Matrix Manipulator

Carroll, [6], uses only serial input/parallel output (SIPO) devices to implement his basic SOP cell shown in Fig. 3.1. It should be noted that although apparently simple, this cell has the disadvantage of producing the elements of the resulting matrix at different time instants. Consequently additional circuitry not shown in the figure becomes necessary in order to store the elements of the resultant matrix for use in other parts of the circuit, or as a final output. To obtain the product of two matrices, one matrix is first loaded by columns and then the second matrix is "paraded" left-to-right by rows, at consecutive clock pulses. The product of an m x p matrix A by a p x n matrix B can be accomplished with p SOP cells in 2m+n-1 clock pulses. This includes the loading of A and the "parading" of B. With reference to Fig. 3.1, if we want to multiply two 2 x 2 matrices

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \tag{3.2.1}$$

A is loaded during the first two clock pulses. During the 3rd clock pulse b_{11} is loaded at input 1 and b_{21} at input 2. The output at t_3 is then c_{11} at output 1, where $c_{11} = a_{11}b_{11} + a_{12}b_{21}$, and zero at output 2. Table 3.1 shows the outputs from t_1 to t_5. Note that five clock pulses are needed, in agreement with

$$\begin{aligned} T &= 2m+n-1 \\ &= 4+2-1 \\ &= 5 \end{aligned} \tag{3.2.2}$$

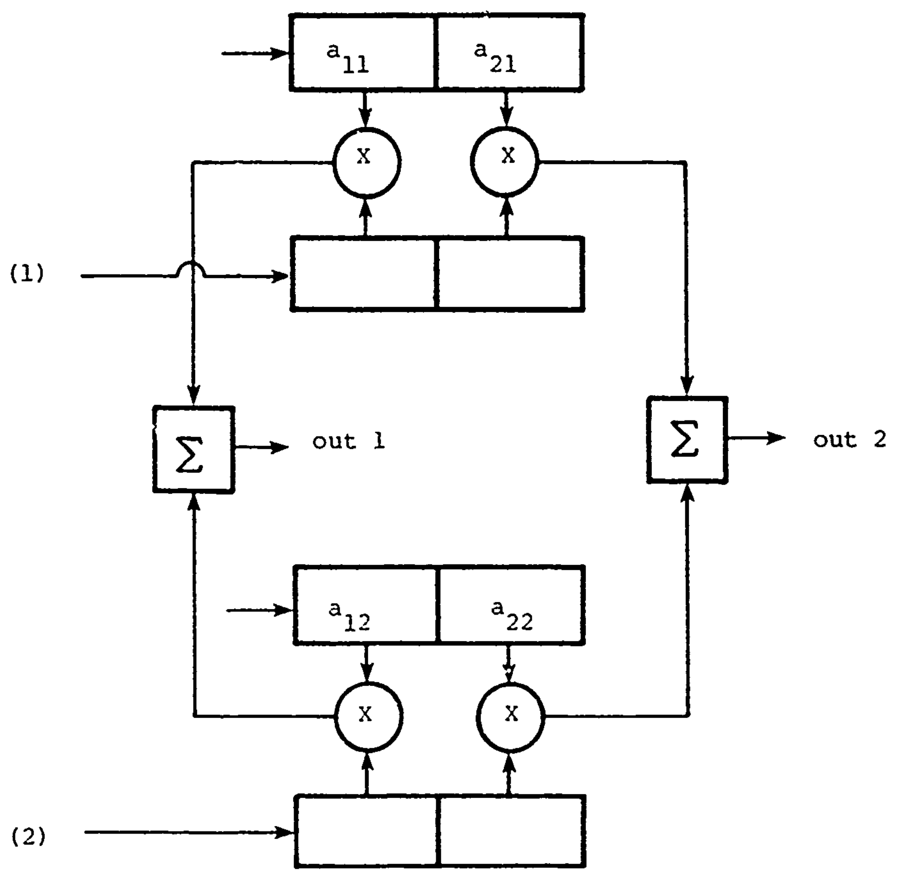


Fig. 3.1 Basic SOP Cell

(1) Load row 1 of matrix [B] starting with b_{11} at clock pulse 1
(2) Load row 2 of matrix [B] starting with b_{21} at clock pulse 1

Exactly the same cell can be used to multiply a q x 2 matrix by a 2 x n matrix. The required time will then be

$$T = 2q + n - 1 \text{ clock pulses} \tag{3.2.3}$$

TABLE 3.1

	t_1	t_2	t_3	t_4	t_5
OUT 1	0	0	c_{11}	c_{12}	0
OUT 2	0	0	0	c_{21}	c_{22}

$\underbrace{t_1 \quad t_2}_{\text{loading A}}$

With reference to the block for the implementation of

$$[P]^+ = \left[P_c^T \; P_c\right]^{-1} \left[P_c\right]^T \tag{3.2.4}$$

given in the previous report and repeated in Fig. 3.2 for convenience, we see that it can be implemented by the circuit of Fig. 3.1, because $[P_c^T P_c]^{-1}$ is 2 x 2 and P_c^T is 2xN. For the subsystem of Fig. 3.2, we had

$$[P_c] = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \\ \cdot & \\ \cdot & \\ \cdot & \\ p_{N1} & p_{N2} \end{bmatrix} \tag{3.2.5}$$

$$[P_c]^T[P_c]^{-1} \triangleq \begin{bmatrix} q_{11} & q_{12} \\ q_{12} & q_{22} \end{bmatrix} \triangleq [q] \tag{3.2.6}$$

$$[P]^+ = \left[\,[P_c]^T[P_c]\right]^{-1} [P_c]^T \triangleq \begin{bmatrix} Q_{11} & Q_{21} & \cdots & Q_{N1} \\ Q_{12} & Q_{22} & \cdots & Q_{N2} \end{bmatrix} \tag{3.2.7}$$

If the system of Fig. 3.1 is used, the operation would require N+3 clock pulses (at frequency NF). Using the circuit of Fig. 3.2 only N clock pulses are required. The CCD devices of Fig. 3.2 are more complex than those of Fig. 3.1, however, but the outputs are all obtained simultaneously by means of analog switches at the parallel outputs of the SIPO devices. SIPO devices can be operated in general at a higher frequency than PISO devices, and if a very high frequency of operation is required, the approach of Fig. 3.1 should be considered.

3.3 Digital/Analog Matrix Manipulator

3.3.1 A Programmable Digital/Analog Correlator

Some of the programmable transversal filters or correlators reported in the literature use digital storage and a simple FET analog multiplier, [3]. As already noted in the previous report, the usefulness of such devices is doubtful. Recently, [8], a different architecture which utilizes digital storage and multiplying DACs has been reported although the most practical approach seems to be the one reported in reference [7]. A programmable digital/analog correlator capable of performing an n-stage programmable correlation which does not require multiplication is shown in Fig. 3.3. The output of this device in the z-domain is

$$\frac{V_{out}(z)}{V_{in}(z)} = H(z) = \sum_{n=0}^{N-1} h_n z^{-n} \qquad (3.3.1.1)$$

where

$$h_n = \sum_{k=0}^{M-1} h_n^k \, 2^{-k} \qquad (3.3.1.2)$$

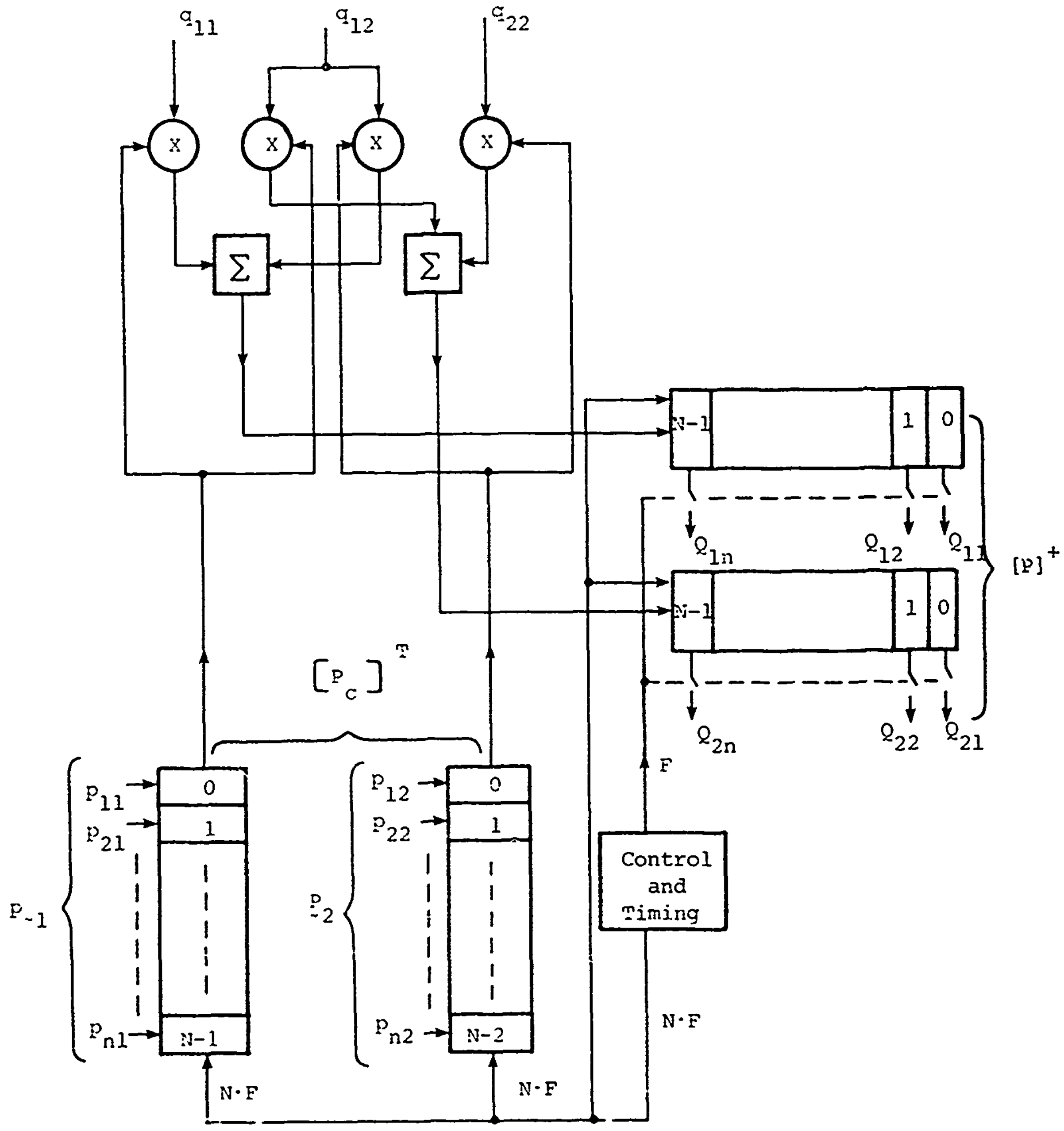


Figure 3.2 The implementation of $[P_c]^+$ using CCDs and Analog multiplier

is the n^{th} weight, represented with M bit precision. Notice that M delay lines and M digital shift registers are needed. The analog signal at each CCD tap output is "multiplied" by the binary value h_n^k (which is either 0 or 1) by either sensing or not sensing each analog charge packet once the n values of V_{in} have been loaded into the CCD device. The 2^{-k} attenuation $(0\leq k\leq M-1)$ at the input of each delay line is achieved by means of capacitive ratio techniques. An off-chip integrating amplifier is used to sum the correlator outputs. The slew rate of this amplifier limited the sampling rate of the correlator reported in [7] to 500 KHz.

3.3.2 Use of the Programmable Digital/Analog Correlator for Matrix Operations

Some of the algorithms described in Chapter V of this report require the computation of image moments of the type

$$M_x = \sum_{i=-m}^{m} \sum_{j=-n}^{n} p'(i,j)x_i \qquad (3.3.2.1)$$

where the windowed image p'(i,j) is of size (2m+1)(2n+1) and x_i is the distance in the x direction from the center of the window. The x_s can then be considered as weights of the image intensities p'(i,j). Formula (3.3.2.1) can be rewritten as

$$M_x = \sum_{i=-m}^{m} p'(i,-n)x_i = \sum_{i=-m}^{m} p'(i,(-n+1))x_i + \cdots + \sum_{i=-m}^{m} p'(i,n)x_i \qquad (3.3.2.2)$$

Each one of the addends in (3.3.2.2) can be obtained with a correlator of the type shown in Fig. 3.3. From (3.3.2.2),

$$M_k \triangleq \sum_{i=-m}^{m} p'(i,k)x_i \quad , \quad -n\leq k\leq n \qquad (3.3.2.3)$$

$$M_x = \sum_{k=-n}^{n} M_k \qquad (3.3.2.4)$$

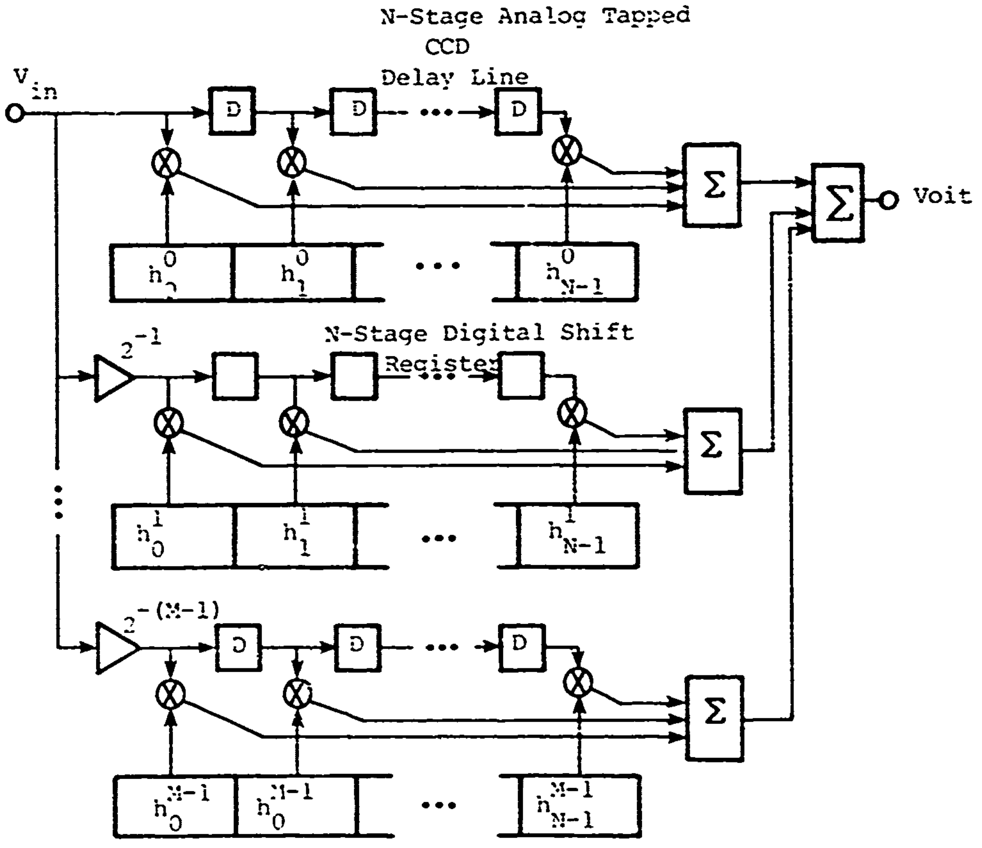


Figure 3.3 A programmable digital/analog correlator

The correlator to implement (3.3.2.3) requires 2m+1 taps for the delay lines and 2m+1 bits for the digital shift registers. The number M of delay lines and shift registers is determined by the required [illegible]racy. A total of 2n+1 correlators is necessary to implement M_x. The final configuration is as shown in Fig. 3.4, where every block has the architecture of Fig. 3.3. Notice that the p'(i,j) are loaded serially into the CCD devices and that x_i, a value known as priori, is loaded only once into the digital shift registers.

The operation performed by the system of Fig. 3.4 is similar to the multiplication of a matrix by a vector. In this case the vector $\underline{x}$ being a constant vector. If it is desired to perform a similar multiplication with a vector of variable elements, an ADC is necessary in order to obtain the digital representation of the vector elements. In addition, each digital shift register would have to be reloaded for each new multiplication. Since the rows of the matrix also have to be reloaded serially into the CCD devices, the processing time would only be slowed down by the A to D conversion time.

3.3.3 Use of the Digital/Analog Correlator for the Implementation of the TSVIP

With reference again to the implementation of the pseudoinverse matrix $[P_c]^+$ in the TSVIP, we have, from (3.2.5) and 3.2.6),

$$[P_c]^+ = \begin{bmatrix} q_{11} & q_{12} \\ q_{12} & q_{22} \end{bmatrix} \begin{bmatrix} p_{11} & p_{21} & \cdots & p_{N1} \\ p_{12} & p_{22} & \cdots & p_{N2} \end{bmatrix}$$

$$= \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1N} \\ c_{21} & c_{22} & \cdots & c_{2N} \end{bmatrix} \qquad (3.3.3.1)$$

where

$$c_{11} = q_{11}p_{11} + p_{12}p_{12}$$

$$c_{12} = q_{11}p_{21} + q_{12}p_{22}$$

$$c_{21} = q_{12}p_{11} + q_{22}p_{12} \quad \text{, etc.}$$

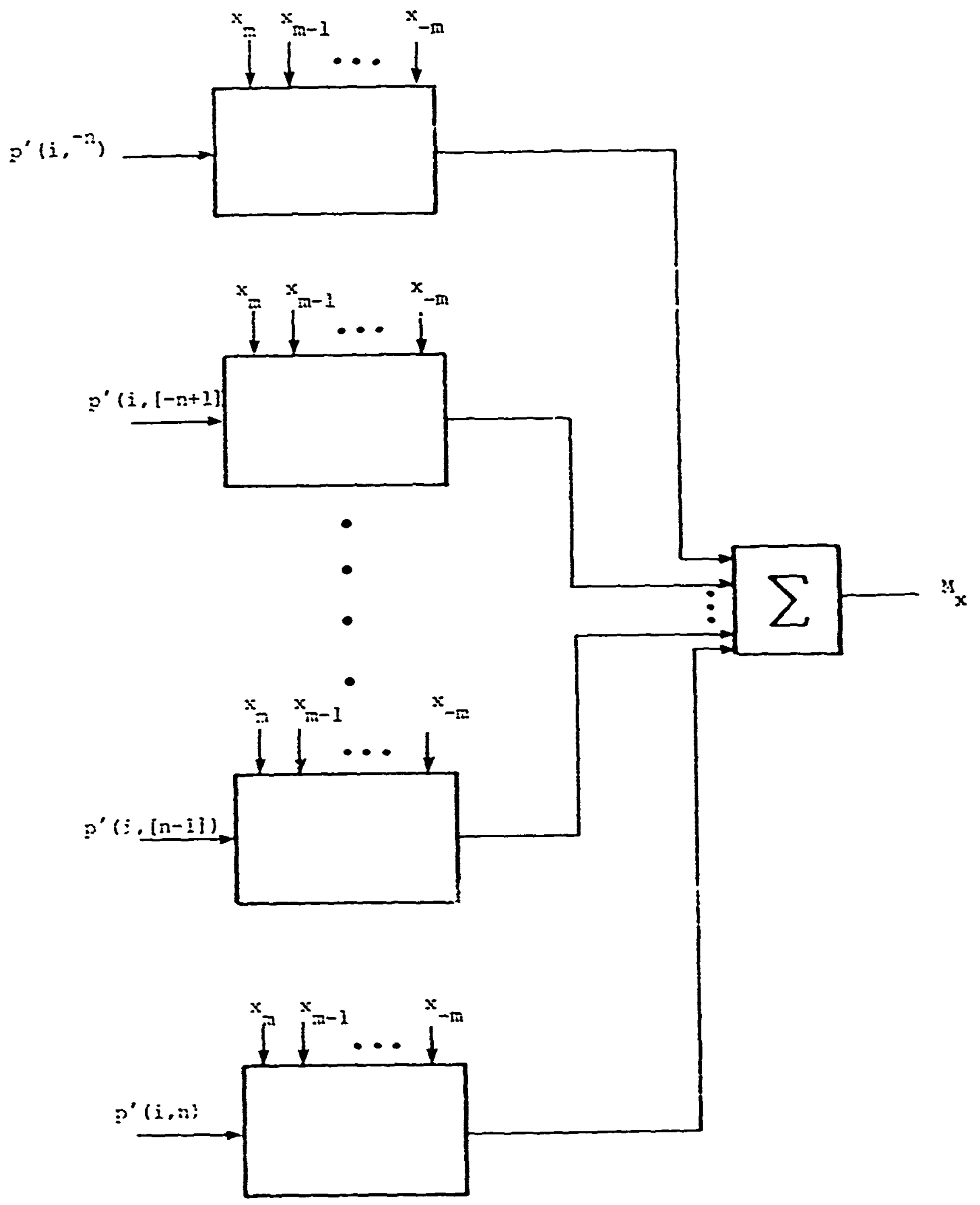


Figure 3.4 System for computing $M_x = \sum_{i=-m}^{m} \sum_{j=-n}^{n} p'(i,j)x_i$

Defining

$$p_{11} = \sum_{k=0}^{M-1} h_{11}^{k}\, 2^{-k} \tag{3.3.3.2a}$$

$$p_{12} = \sum_{k=0}^{M-1} h_{12}^{k}\, 2^{-k} \tag{3.3.3.2b}$$

$$p_{jm} = \sum_{k=0}^{M-1} h_{jm}^{k}\, 2^{-k} \qquad j = 1,2\ ;\ m=1,2,\ldots,N \tag{3.3.3.2c}$$

the matrix multiplication (3.3.3.1) can be expressed in terms of the multiplication of the 2 x 2 matrix [q] and the vectors

$$\underline{p}j \triangleq \begin{bmatrix} p_{j1} \\ p_{j2} \end{bmatrix} \quad , \ j = 1,2,\ldots,N \tag{3.3.3.3}$$

as follows,

$$\underline{c}j \triangleq \begin{bmatrix} c_{1j} \\ c_{2j} \end{bmatrix} = \begin{bmatrix} q_{11} & q_{12} \\ q_{12} & q_{22} \end{bmatrix} \begin{bmatrix} p_{j1} \\ p_{j2} \end{bmatrix} \quad , \ j = 1,2,\ldots.N \tag{3.3.3.4}$$

Hence,

$$[p_c]^{+} = [\underline{c}_1\ \underline{c}_2\ \underline{c}_3\ \cdots\ \underline{c}_N] \tag{3.3.3.5}$$

The element c_{11} of $\underline{c}_1$ can be implemented as shown in Fig. 3.5. The element c_{12} of $\underline{c}_1$ is implemented by exactly the same architecture with the input to the delay line changed to q_{12}, q_{22} instead of q_{11}, q_{12}. For both elements, the input to the ADC is p_{11}, p_{12}, sequentially, which indicates that only one ADC is needed for each $\underline{c}_1$. Notice that the timing must be such that when q_{11} is the output of the delay and q_{12} is at the input to the delay, p_{11} must have been converted and shifted to the right, and p_{12} must have been converted, as indicated in Fig. 3.5. Notice also that the hardware could be reduced by half, since q_{11}, q_{12} and q_{22} could be entered sequentially (here the symmetry of the matrix allows us to use three inputs, instead of four) to the delay, producing c_{11} and c_{12} sequentially at the output. The processing time would, however,

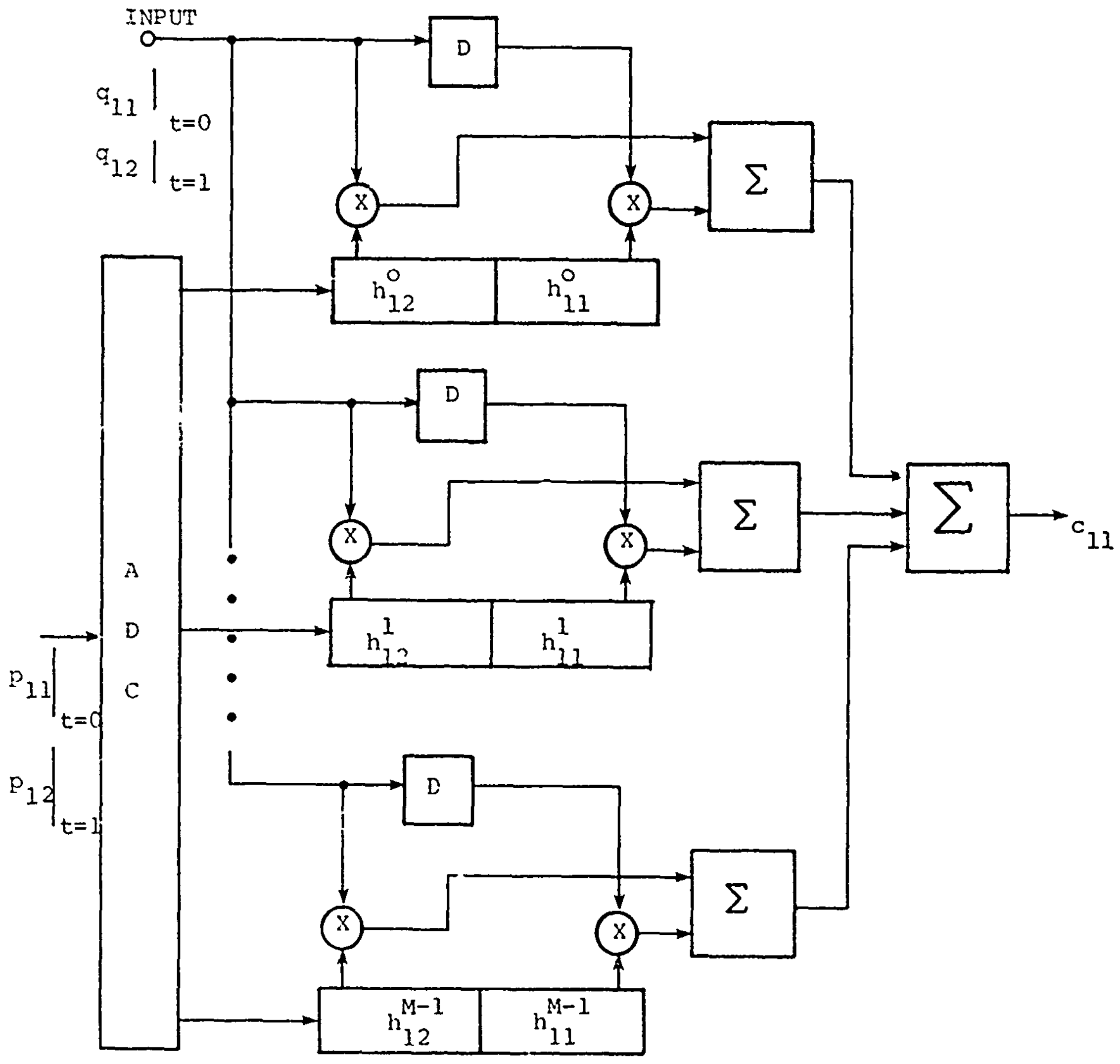


Figure 3.5 Digital/analog implementation of element c_{11} of matrix $[p_c]^+$

be larger, and means of storing c_{11} while c_{12} is being computed would be necessary.

If the parallel approach is used, 2N blocks are needed. If the sequential approach is used, N blocks are needed, plus the extra circuitry necessary to store c_{1n} while c_{2n} is being computed. The all parallel block diagram is shown in Fig. 3.6.

Another possibility is the all-serial processor, in which a single block of the type shown in Fig. 3.5 is used. The $\underline{p}_j$s are converted and loaded sequentially into the digital shift register, from j=1 to j=N. For each $\underline{p}_j$, q_{11}, q_{12} and q_{22} are loaded sequentially into the CCD delay line, and the multiplication performed. The elements of the matrix $[P_c]^+$, c_{jk}, appear sequentially at the output of the device and must be stored. The processing time will be N times larger than that for the parallel-serial processor, but the hardware will be reduced from N to 1. Notice that only one ADC is necessary in this case. The times required for the three cases are:

a) All parallel processor,

$$T_p = (ADC)_{time} + 2t \qquad (3.3.3.6)$$

where t is a clock pulse time.

b) Serial-parallel processor,

$$T_{sp} = (ADC)_{time} + 3t \qquad (3.3.3.7)$$

c) All-serial processor,

$$T_s = N\cdot(ADC)_{time} + N\cdot 3t \qquad (3.3.3.8)$$

$$= N\cdot T_{sp}$$

From the point of view of speed, the serial-parallel processor represents the best approach, because it requires considerably less hardware than the all-parallel, with a very small increase in processing time.

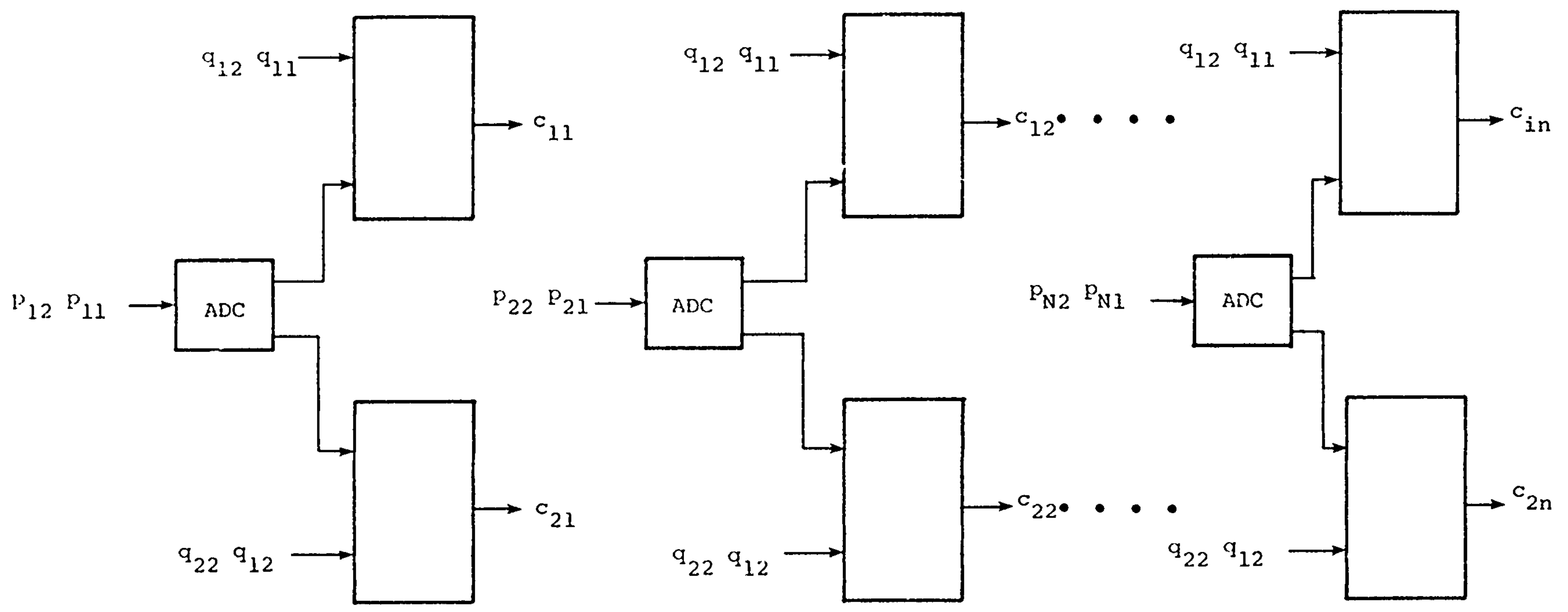


Figure 3.6 All parallel digital/analog processor (timing not indicated)

For the all-analog system of Fig. 3.2, N clock pulses at a frequency F are needed for one computation. In that case it was assumed that the PISO devices could operate at a frequency NF. If the same assumption is made for the digital/analog system, the all serial processor would require a time equal to 3 clock pulses of the basic frequency F plus N times the ADC time. High speed ADCs have conversion rates of about 100 ns for 8 bit accuracy. For a basic frequency of 1 MHz and N = 9, the all serial processor could compete in speed with the all-analog processor. It must be emphasized that if higher basic frequency rates are used, or N is much larger than 8, the all-serial processor will require considerably larger time than the all-analog if state-of-the-art ADCs are used. The serial-parallel processor time will be considerably smaller than the all-analog time (for a basic f = 1 MHz), but it must be remembered that N ADCs would be necessary.

3.4 MOS Analog Multiplier Compatible with CCD Structures

The implementation of the analog TSVIP requires on-chip analog multipliers and op amps. The CCD structures use MOS technology, and consequently the design of the chip will be simplified if the multipliers and op amps use the same technology. Several NMOS high performance op amps have been reported in the literature, [9].

A four quadrant NMOS analog multiplier which seems adequate for our application was designed by Bosshart, [10] for a CCD signal processor. The basic structure of the multiplier is given in Fig. 3.7. The transistors are n channel MOS enhancement type devices. Recall that the output of CCD cells have dc bias level, and the inputs to the multipliers come directly from CCD taps. The voltages V_{IN_1} and V_{IN_2} will then vary with the signal about the dc bias level, but will never become negative. Q_1 and Q_2 are biased by V_{DD}, V_{SS}

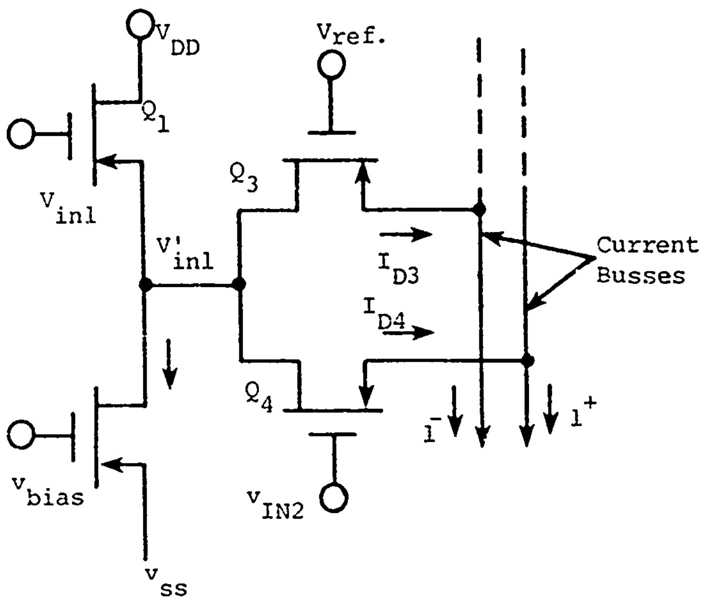


Figure 3-7 nMOS Multiplier Basic Cell

Note: $V_{in1} = V_{dc\ bias\ 1} + V_{in1}$

$V_{in2} = V_{dc\ bias\ 2} + V_{in2}$

and V_{bias} to work in the saturation region, Q_2 acting as a current source and Q_1 as a source follower. Q_3 and Q_4 must work in the "triode" region (the essentially linear region before saturation), and they work as voltage controlled resistors. Their V_T must be large. If the busses to which the sources of Q_3 and Q_4 are connected are at a potential equal to the dc bias at the output of the CCD devices, the V_{DS} for these two transistors will be equal to V_{in_1} because the output voltage of Q_1 is practically the same as its input voltage.

For Q_3 and Q_4 the drain current is given by

$$I_{D_3} = B\ (V_{ref} - V_T)V_{DS} - \frac{1}{2}V_{DS}^2 \tag{3.4.1}$$

$$I_{D_4} = B\ (V_{IN_2} - V_T)V_{DS} - \frac{1}{2}V_{DS}^2 \tag{3.4.2}$$

The summation of I_{D_4} and $(-I_{D_3})$ is then

$$I_{D_4} - I_{D_3} = BV_{in_1}(V_{IN2} - V_{ref}) \tag{3.4.3}$$

If V_{ref} is made equal to the dc bias level of V_{IN_2}, we see from (3.4.3) that

$$I_{D_4} - I_{D_3} = BV_{in_1}V_{in_2} \tag{3.4.4}$$

This basic multiplier produces distortion terms due to the high output impedance of the CCD devices which drive Q_4, the output impedance of Q_1, etc. It is possible to correct these errors by adding extra components to the circuit, such as a source follower between the output of the CCD and the gate of Q_4, or the error terms could be corrected, as suggested in [10] by performing a weighted summation of I_{D_4} and $-I_{D_3}$. The only way of checking the performance of the device is by means of a prototype, although an extensive theoretical analysis taking all these factors into consideration could be performed. For a channel length of 1.5 μm, well within present technology limits, the maximum bandwidth of the device is 5 MHz.

3.5 Experimental Results for the Multichip Implementation of $[P_C]^+$

3.5.1 Introduction

Although the eventual goal of this research is to design and construct the CCD processor in a single chip or, if this is not possible, in a minimum number of chips, it was desirable at this time to test the feasibility of the CCD implementation by constructing one of the TSVIP blocks using commercially available CCD devices, multipliers and op amps.

With reference to Fig. 3.2, we see that the implementation of $[P_c]^+$ requires the use of two PISO CCD devices, two SIPO CCD devices, four analog multipliers, and two summers. The use of commercially available CCD devices plus the requirements presented by variable matrix operations, resulted in some problems which can be easily avoided when CCDs are used to implement transversal filters or discrete correlators.

To our knowledge only EG&G Reticon produces commercial SIPO and PISO CCD devices at present. These devices have an output dc bias level of about 9.5 V for the SIPO and 5 V for the PISO. The output signal appears superimposed to this bias. For the Reticon TAD-32 SIPO device, the input signal can have a maximum value of 3 V pp. If a higher amplitude is input, the positive swing of the outputs is clipped, due to the dc bias. For transversal filters and other single output applications, the dc bias can be eliminated at the output by means of a simple resistor-difference amplifier circuit, [11]. For our application, however, in which the N outputs have to be used individually, a dc bias elimination circuit would have to be used at each tap. In an integrated circuit processor this would not be a difficult requirement, because only a few transistors and resistors with values convenient for integration are needed. If discrete components are involved, as in our experimental circuit, the resultant circuit would be too bulky. A simple approach, not convenient in practice, was used in our circuit, which will be explained in section 3.5.2.

Another problem is presented by noise introduced by the sampling process. Observations very similar to those made above apply also in this case. In transversal filters, the noise can be filtered once at the output. The sampling noise can be explained graphically by means of Figs. 3.8(a) and (b). In Fig. 3.8(a), the lower trace is a sinusoidal input at 500 Hz, sampled at 500 KHz. The upper trace is the output at tap 1. The noise is inherent to the sampled operation of the CCD in which a "piece" of the input is transferred at each clock pulse. The sweep in Fig. 3.8(a) is at 1 ms/div, while in Fig. 3.8(b) the same two signals are shown with the sweep at .5 μs/div. The notch at the tap #1 output is due to the sampling-holding-transferring and shows up as noise.

3.5.2 Experimental Circuit

As mentioned in the previous section, the experimental circuit was constructed using multiple chips. Four vector boards were used, one for the PISO circuit, one for the multipliers/adders circuit, one for the SIPO circuit, and one for the clocks. The PISO devices are the Reticon R5501. As can be seen in Fig. 3.9, two bias voltages are required for these devices. The value of the bias voltages affects the maximum allowable peak to peak value of the signal. Bias voltages were adjusted for optimal operation. The R5501 requires three clocks, $\emptyset_1$ and $\emptyset_2$ which are the complement of each other and which work at the frequency of transfer, and $\emptyset_T$ which works at the loading frequency. One $\emptyset_T$ pulse is required for every 32 $\emptyset_2$ pulses, because the device has 32 parallel inputs. This is in accordance with the F and NF frequencies indicated in Fig. 3.2. In a custom made device the number of parallel inputs would be N.

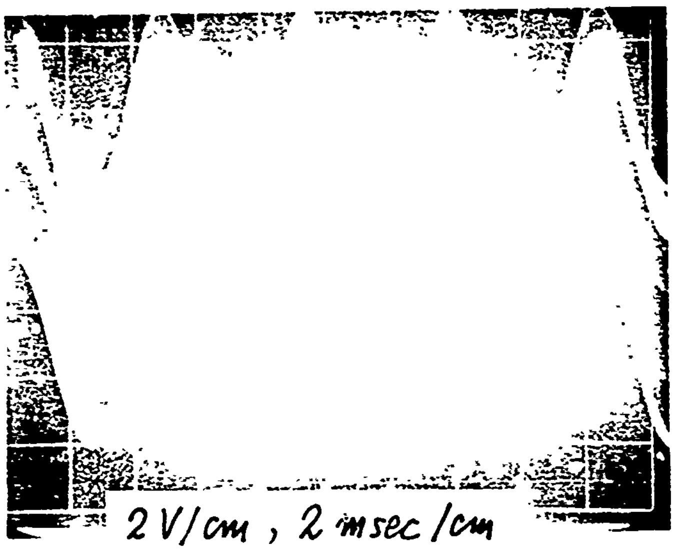


Fig. 3.8(a) Output At Tap 1 And Input, SIPO Device.

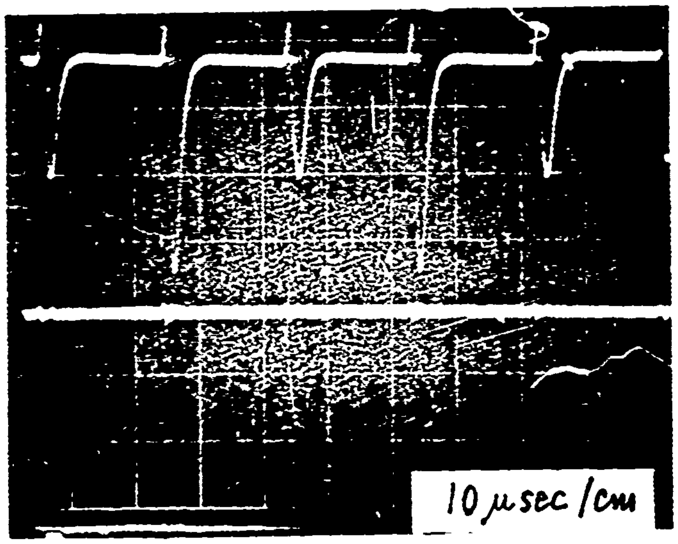


Fig. 3.8(b) Sinusoids Of Fig. 3.8(a) With A Much Shorter Sweep Time

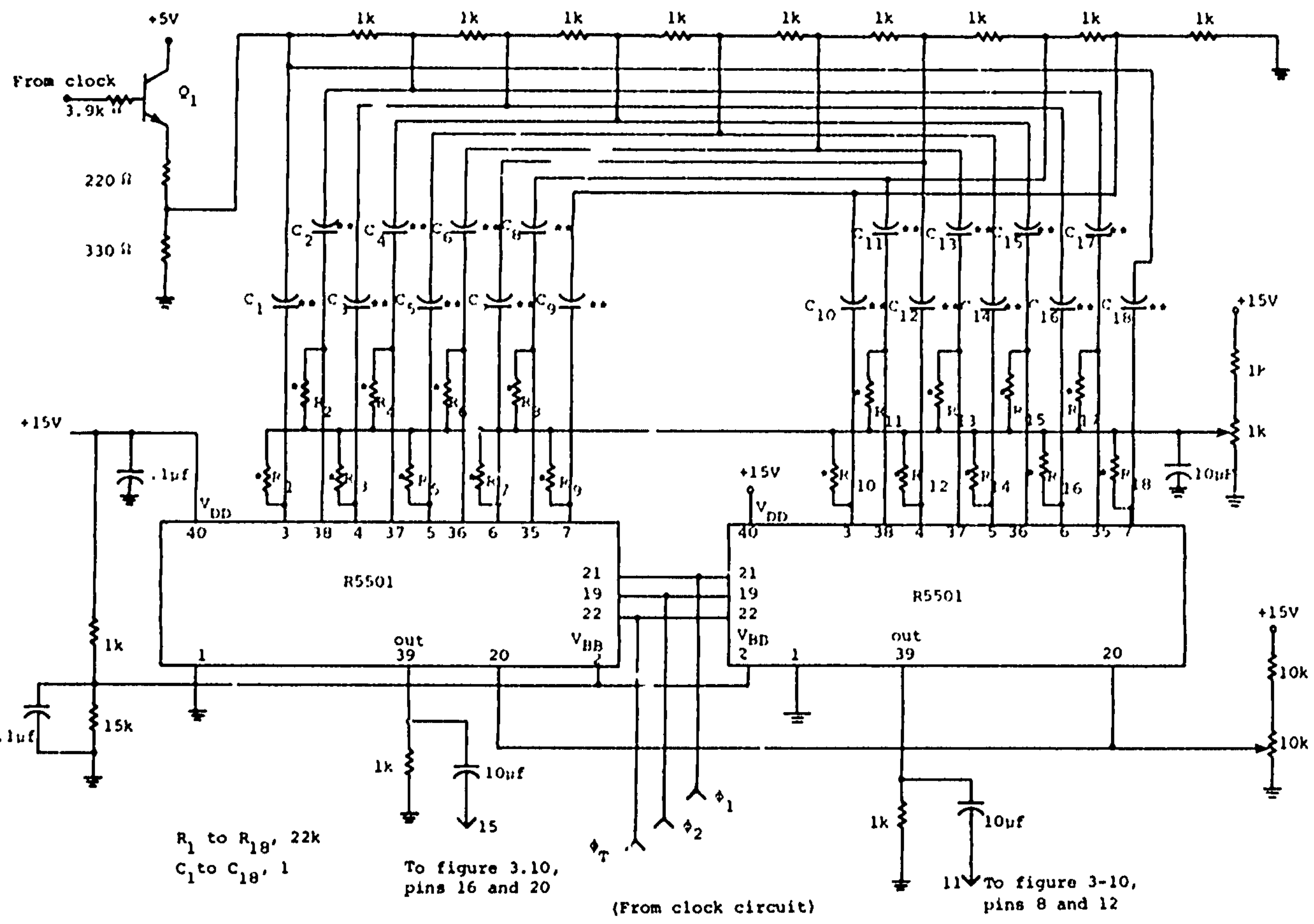


Figure 3·9 FISO Devices Circuit Diagram

In the Reticon device loading is effected when $\emptyset_T$ and $\emptyset_2$ are high, but $\emptyset_T$ must start at least 50 ns before and end at least 50 ns after the corresponding $\emptyset_2$ pulse. A combination logic TTL circuit was designed to obtain $\emptyset_T$, $\emptyset_1$ and $\emptyset_2$ from a single external clock signal. The signals are transferred entirely out of the CCD device during the next 32 clock pulses of $\emptyset_2$ and $\emptyset_1$, when $\emptyset_1$ is high and $\emptyset_2$ is low. The sampled signals are first stored in the input capacitors, and then transferred into the delay line. This process has an effect in the output, as will be seen later.

The specified maximum frequency for the R5501 is 5 MHz,[12],althouth the performance of the devices degrades quickly for $f > 2$MHz. Consequently, NF was chosen to be 1 MHz, with F = 31.25 KHz. This is well below the frequency specified in the previous report, but it is the best achievable with available devices. In general SIPO devices perform better than PISO, and as was suggested in Sect. 3.2, it could be more convenient to use SIPO devices only in the SOP configuration to implement the processor. The lack of time and of the required parts prevented the testing of this architecture.

The SIPOs used in the experimental circuit also present the problem of sensitivity to bias voltages, and these were adjusted for optimal operation. The circuit for the SIPO CCDs is given in Fig. 3.11.

The multiplier chips chosen were the AD533, with a maximum error of less than .5% of full scale, and a small signal unity gain of 1 MHz. The summers were implemented using the AD 507J op amp which has a 100 MHz GBW product, a 25 V/us minimum slew rate, and a unity gain BW of more than 10 MHz. The circuit is given in Fig. 3.10.

With reference to Fig. 3.2, we see that the dc bias at the output of the PISO devices must be blocked before the signals are inputted to the multipliers.

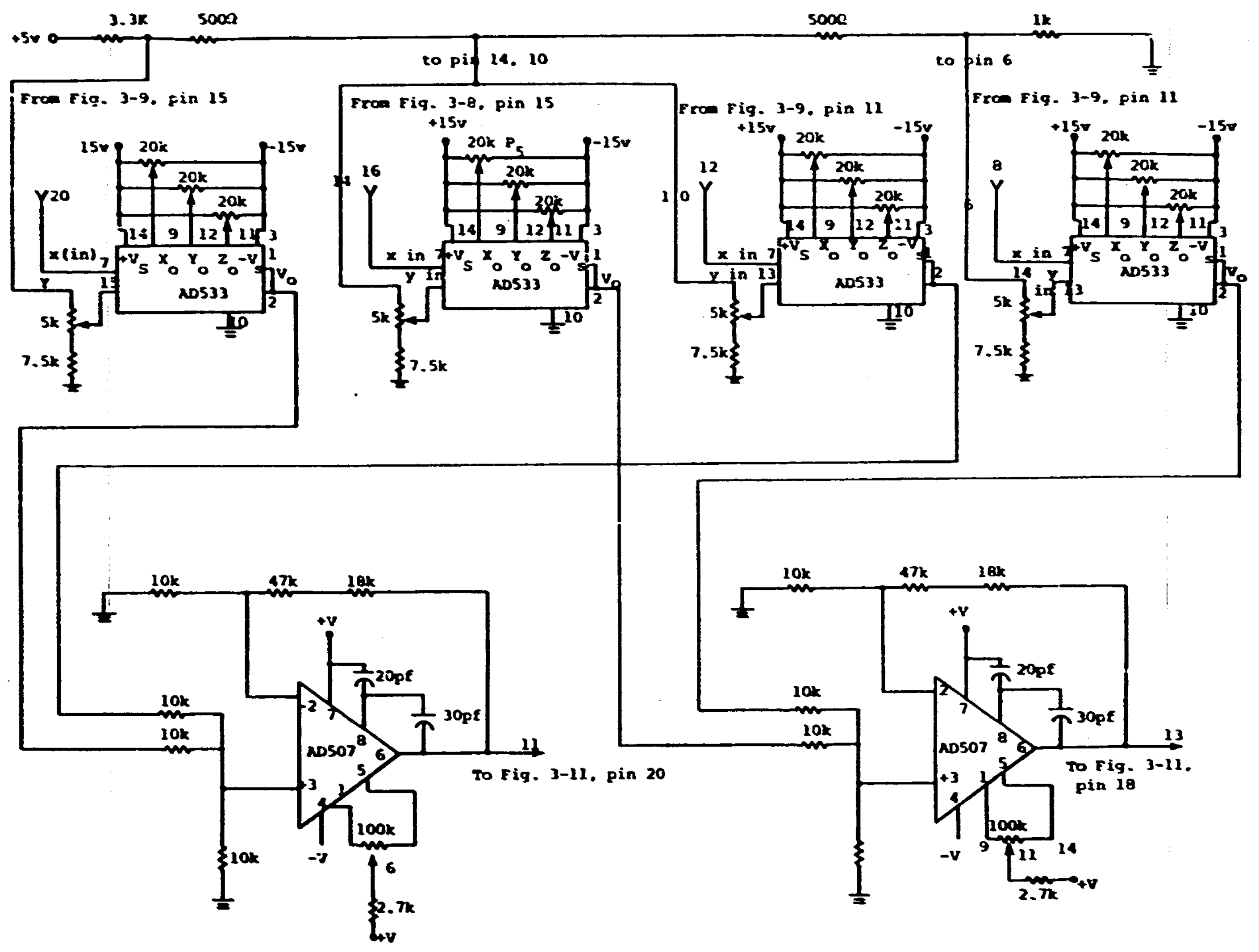


Figure 3.10 Multipliers and Summers Circuit Diagram

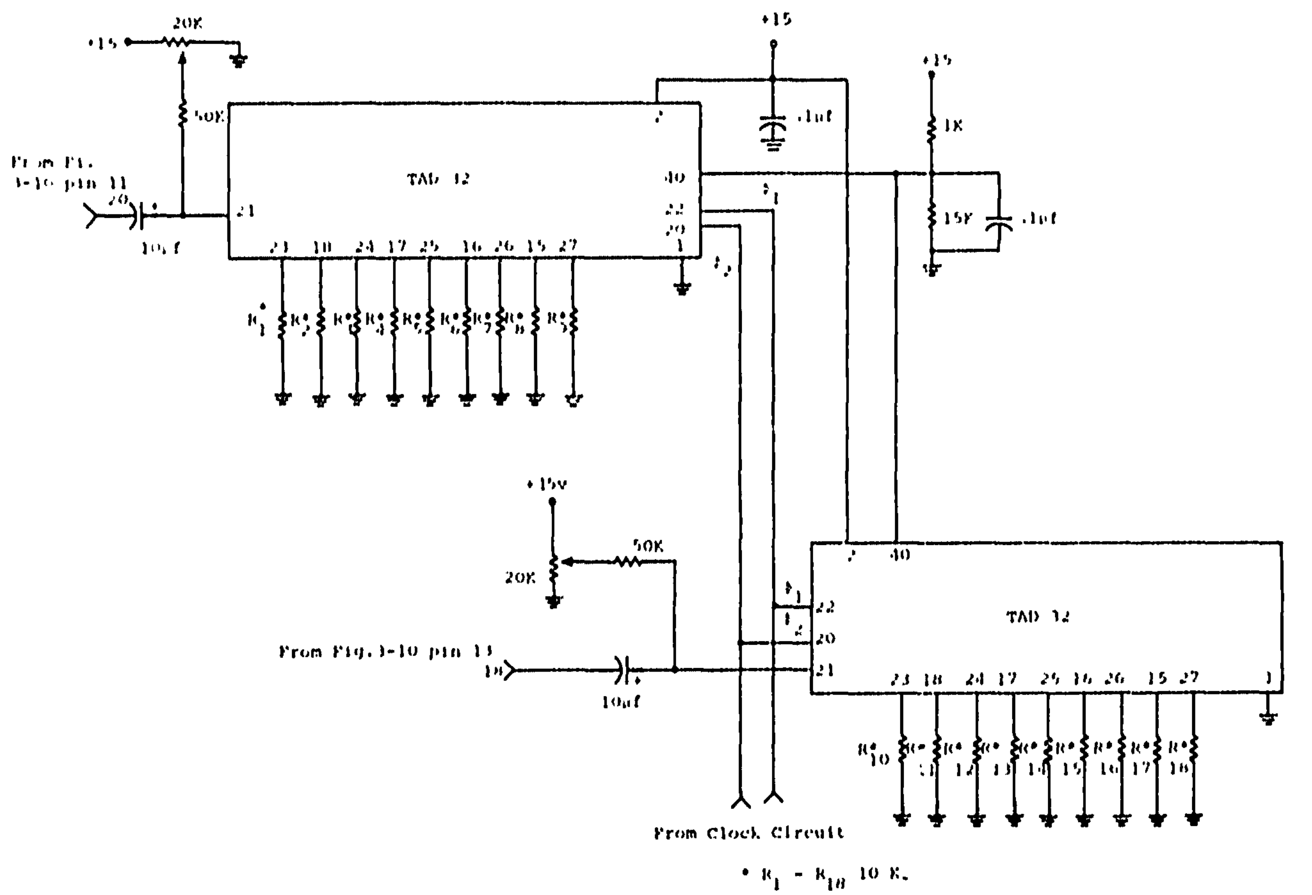


Figure 3.11 SIPO Devices Circuit Diagram

As already mentioned, the discrete circuit implementation of a resistive network/ differential amplifier circuit would be too cumbersome for this purpose. For this qualitative study, a simple blocking capacitor was used.

In order to test the devices qualitatively, a staircase voltage from -0.22 V to -2.0 V in steps of 0.22 V was applied to taps 1 through 9 of the PISO device No 1, and a staircase from -2 V to -0.22 V to the PISO device No 2 taps 1 to 9. With reference again to Fig. 3.2, q_{11} was chosen as 2 V dc, q_{12} as 1.5 V dc and q_{22} as 1 V dc. The input voltages to the first nine taps of the PISO devices can be expressed as follows,

$$V_1 = -mx \tag{3.5.2.1}$$

$$V_2 = -2 + mx \tag{3.5.2.2}$$

where m = 2/9 is the ramp slope and x is the tap number. Multiplication by the constant "q" inputs to the multipliers only changes the scaling of these voltages, and addition of the multipliers outputs produces another straight line staircase,

$$\begin{aligned} V_{M_1} + V_{M_2} &= -m_1x - K + m_2x \\ &= -K + (m_2 - m_1)x \end{aligned} \tag{3.5.2.3}$$

Waveforms for the experimental circuit are shown in Figs. 3.12 to 3.14. In Fig. 3.12(a), the upper trace shows the $\emptyset_T$ clock pulse. The lower trace shows a few $\emptyset_2$ clock pulses. The time relation between $\emptyset_T$ and $\emptyset_2$ shows clearly. Fig. 3.12(b) shows the output of PISO device No 1. This waveform corresponds to expression (3.5.2.1). The split of each of the nine steps into two levels is inherent to the operation of the R5501, and is due to the two step storage-transfer operation for $\emptyset_2$ high and $\emptyset_1$ high, respectively. The output of the multipliers should be filtered in the final version of the processor, in order

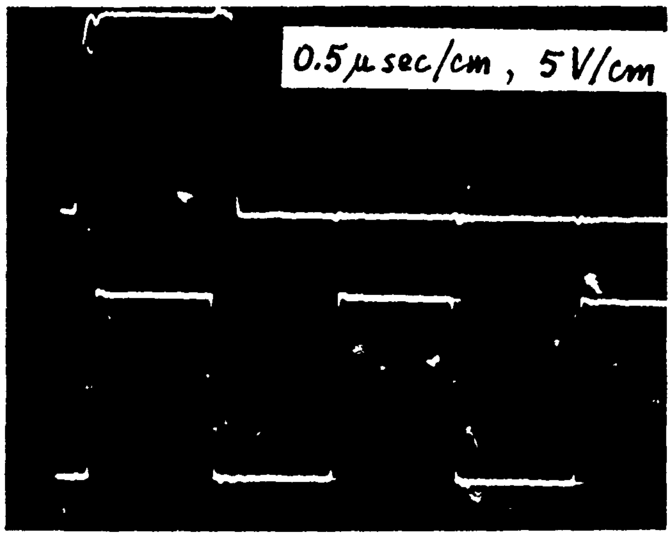


Fig. 3.12) $\emptyset_T$ And $\emptyset_2$ Waveforms 5V/cm; Sweep At 0.5 μs/cm.

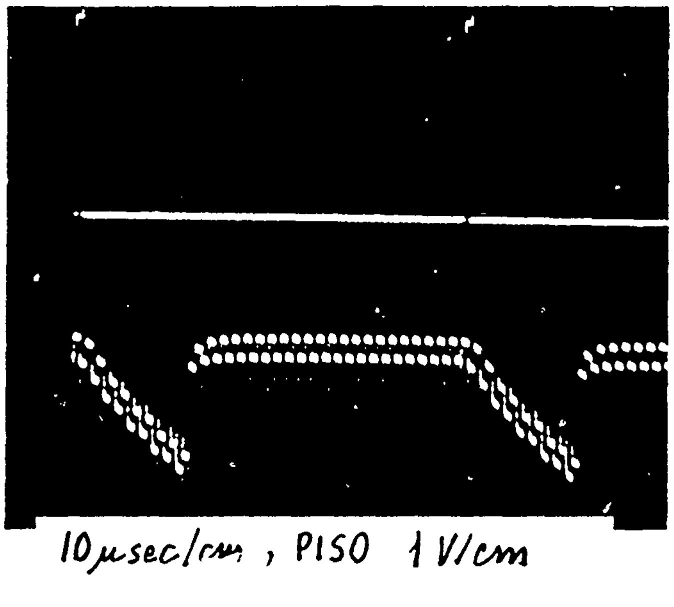


Fig. 3.12(b) $\emptyset_T$ Clock And Output Of PISO Device No 1.

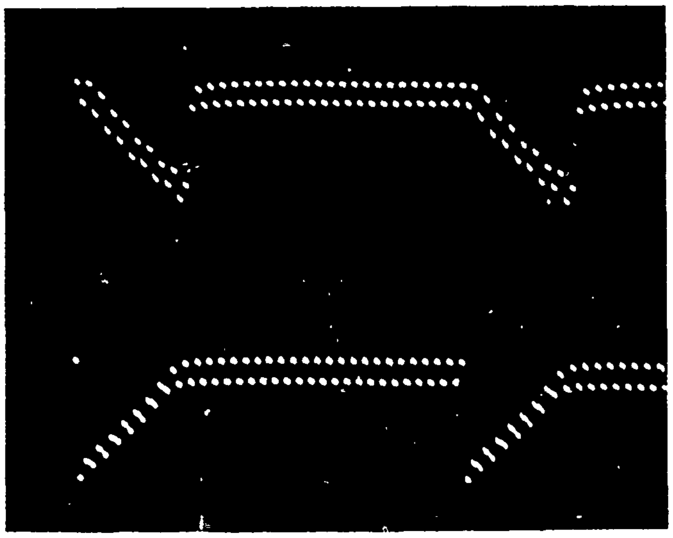


Fig. 3.13(a) PISO Devices Output

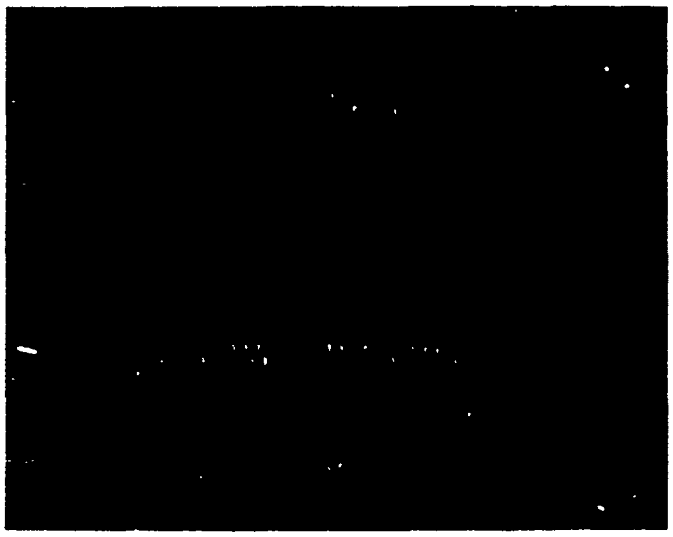


Fig. 3.13(b) First Two Multipliers Output

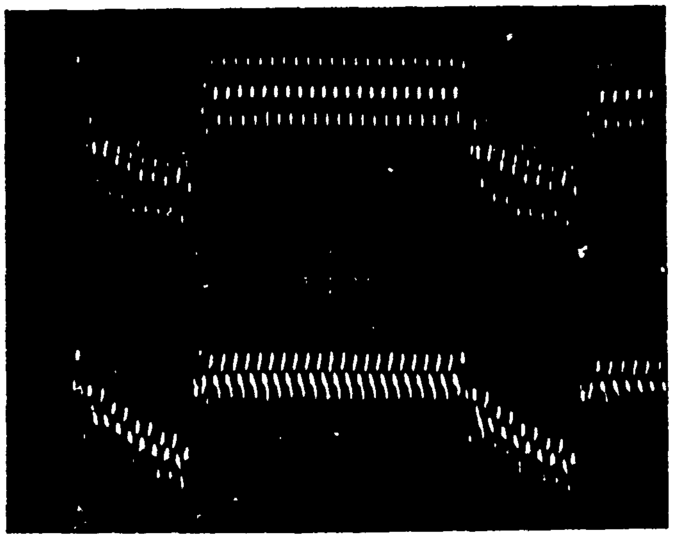


Fig. 3.14(a) Output Of Summers

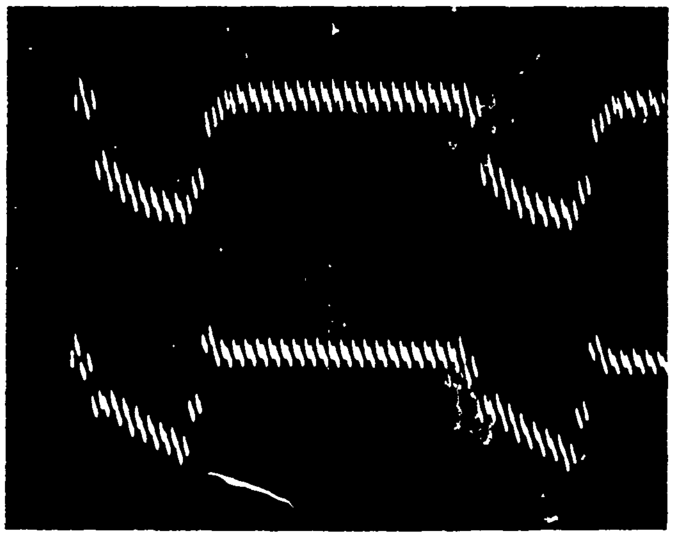


Fig. 3.14(b) SIPO Devices Output At Taps No 9.

to avoid higher noise and distortion in successive stages. Fig. 3.13(a) shows the outputs of PISO devices 1 and 2 (upper and lower traces, respectively). Fig. 3.13(b) shows the output of the first two multipliers of Fig 3.2. At this point noise becomes more evident due to the two different levels for each output pulse of the PISO devices. The waveforms have the correct shape, however.

Noise and distortion increase significantly at the output of the summers, Fig. 3.14(a). In addition to the sources of noise mentioned above, the use of several boards introduces grounding problems which would be eliminated in an improved version or in a single chip design of the device. Finally, in Fig. 3.14(b) which shows the output at tap 9 of the SIPO devices, although the general shape of the expected signal is preserved, noise and distortion have increased further.

In spite of the high noise and distortion levels, this experimental version of the pseudo inverse $[P_c]^+$ block succeeded in showing that it is possible to implement the TSVIP by means of CCD devices and other analog devices.

3.5.3 Conclusions and Recommendations

The main sources of error in the implemented block are:

(a) Coupling capacitors which change the dc level at the input to the multipliers by an amount corresponding to the average value of the ac signal.

(b) Noise due to sampling-storage-transfer in the CCD devices.

(c) Ground problems due to the multi-board implementation, multiple power supplies and the necessity of three clocks.

This was a simple experimental version of the subsystem using readily available components and many discrete parts (resistors, capacitors, etc.). Noise and distortion could be drastically reduced in a system using specially designed CCD devices and a high degree of integration. The use of SOP architecture which allows implementation using only SIPO devices (plus multipliers) should be considered, due to the higher performance of SIPO devices.

The Reticon devices are surface charge devices. The design should be based on buried channel ("peristaltic") devices, which do not need a "fat zero" (i.e., an input dc bias level) and have higher speeds, better charge transfer efficiency and a larger dynamic range than surface channel devices [13.14].

CHAPTER IV

THE USE OF SEQUENTIAL ESTIMATION TECHNIQUES IN IMPLEMENTING THE TSVIP ALGORITHM

4.1 Introduction

4.1.1 Background

The TSVIP algorithm reduces the problem of image tracking to a problem in linear estimation [5]. The method by which this linear estimation is performed determines the speed and ease with which the TSVIP algorithm can be implemented. A linear estimation procedure which can be performed rapidly, but is difficult or impossible to implement with the desired circuit technology is useless. Likewise, an estimation procedure which lends itself to easy implementation with the desired technology, but is temporally inefficient is also of no use.

Charge coupled devices (CCDs) are the devices with which it is desired to implement the tracking processor. As pointed out elsewhere in the report, CCDs have been selected because of their size, low power consumption, reliability and speed [14]. It is anticipated that an entire image tracker including a CCD imager could be constructed on one VLSI integrated circuit. While a clock rate of from 1 to 50 MHz would be sufficient for a tracking processor, using the solution approach discussed in this chapter, experimental CCDs have been clocked at up to 1 GHz. Results of this sort certainly make it desirable to find a linear estimation procedure which lends itself to easy implementation with CCDs.

4.1.2 Closed Form Techniques

Two estimation procedures which meet the first criterion of speed are the matrix inverse and the generalized inverse applied to square and overdetermined systems, respectively [15]. The matrix inverse provides an estimate with no associated error, while the generalized inverse provides an estimate whose associated total squared error is minimized. The matrix inverse is of little use since only overdetermined systems are anticipated. The main drawback of these techniques is that both require a matrix inversion which is difficult if not impossible to perform totally with CCDs (multipliers may be required). Therefore, it is necessary to look beyond these closed-form procedures for a suitable estimation procedure.

4.1.3 Sequential Procedures

Sequential procedures are a class of estimation procedures which satisfy the second of the aforementioned criteria. They call for just the sort of linear combinations of discrete-analog sequences that CCDs are able to provide. This makes sequential estimation procedures better suited to CCDs than the closed form procedures.

A sequential estimation algorithm is a recursive procedure which, using an initial "guess," converges to a solution of a system of a linear equations which minimizes a chosen criterion function. Most often the total squared error associated with the estimate is chosen for the criterion function. Sequential estimation procedures which minimize a squared-error criterion function can be shown to converge to the same solution as the generalized inverse as the number of recursions performed becomes infinite . For practical reasons, recursion is terminated after a reasonably accurate solution has been obtained. The usefulness of a sequential procedure is severely limited if a large number of recursions is required to arrive at an acceptable estimate of the solution to a system of linear equations. A judicious choice of the starting "guess" and the use of convergence acceleration techniques (to be subsequently discussed) can be of some help. However, the utility of sequential estimation procedures in implementing the TSVIP algorithm is extremely dependent on the speed with which the procedures converge.

4.2 Minimum Squared-Error Descent Procedures

4.2.1 Introduction

The sequential estimation techniques chosen for investigation are known as minimum squared-error descent procedures. These sequential estimation procedures use the gradient descent method to minimize the squared-error associated with the solution. Their suitability for CCD implementation makes them attractive for use in a target tracking processor.

The problem which must be solved is

$$d = Da \tag{4.2.1.1}$$

where

d is the $N \times 1$ scene difference vector,

D is the $N \times 6$ matrix of weighted and unweighted spatial derivatives,

a is the 6×1 vector of the affine transform coefficients (the quantity it is desired to estimate), and N is the number of target points used in the tracking calculation.

An estimate of the a vector which minimizes some function of the error between Da and d is sought. An error vector can be defined as

$$e = Da - d \tag{4.2.1.2}$$

The square of the total length of the error vector is then given by

$$\begin{aligned} J(a) &= \|Da - d\| \\ &= \sum_{k=1}^{N} (a^t D^k - d^k)^2 \end{aligned} \tag{4.2.1.3}$$

where

D^k is the transpose of the k'th row of the D matrix,

d^k is the k'th element of the d vector,

a^t is the transpose of the affine transform coefficient vector.

It is this function which we wish to minimize in obtaining a "good" estimate of the vector a. A gradient descent procedure can be used to produce a sequence of vectors which will eventually converge to a solution minimizing J(a). The form of a general gradient descent (also known as steepest descent) is given by

$$a_{k+1} = a_k - p_k \nabla J(a_k) \tag{4.2.1.4}$$

where

a_k and a_{k+1} represent the k'th and k+1'th estimate of a, respectively.

p_k is a positive scale factor which adjusts the step size [16].

The initial estimate a_0 is chosen arbitrarily unless a priori information is available to provide a reasonable guess. At each iteration of the descent procedure a fraction of the error gradient is subtracted from the previous estimate of a. If a_k is thought of as a point in the multi-dimensional a vector space, then the subtraction of a fraction of the error gradient represents a movement, in the vector space, in the direction of the maximum decrease in the magnitude of the chosen error criterion. Thus, each step is thought of as a downward movement in the direction of the location of the a vector which minimizes J(a). Thus, the name "descent procedure."

4.2.2 <u>Multi-Sample Algorithm</u>

In this case the gradient of the criterion function J(a) is given by

$$J(a) = \sum_{k=1}^{N} 2(a^t D^k - d^k) D^k = 2D^t(Da - d) \tag{4.2.2.1}$$

Inserting this result into equation (4.2.1.4) gives the descent algorithm

$$a_{k+1} = a_k - p_k D^t (Da_k - d) \tag{4.2.2.2}$$

It can be shown that if p_k is chosen to be p_1/k, where p_1 is a constant usually less than 1, this descent algorithm, which will be called the multi-sample algorithm, satisfies

$$D^t(Da - d) = 0 \qquad (4.2.2.3)$$

Thus, this descent algorithm will determine a coefficient vector a which minimizes the total-squared length of the error vector.

An algorithm of this sort does fulfill the requirement of not requiring a matrix inversion. The multi-sample algorithm also satisfies the speed of convergence requirement previously discussed. Its main drawback is that its CCD implementation, while not impossible, would be very hardware intensive. The size of the D matrix, N, would determine the number of tapped delay lines (the basic CCD "building block") required to implement this algorithm. Thus, the number of target points used in tracking would determine the size of the processor. This is not desirable and necessitates looking further for a more suitable version of the descent procedure.

4.2.3 The Widrow-Hoff Rule

The error criterion used in arriving at the multi-sample descent algorithm represents, except for a constant multiplier, the average squared length of the error vector associated with estimate a_k. The movement at each iteration is in the direction of the maximum decrease in the average length of the squared error vector. Widrow and Hoff [17] introduced the idea of substituting individual error vectors for the average error vector. This allows the rows of the D matrix to be considered individually and leads to the LMS or Widrow-Hoff Rule

$$a_{k+1} = a_k + p_k(d^k - a_k^t D^k)D^k \qquad (4.2.3.1)$$

This descent procedure allows the rows of the D matrix to be considered sequentially. If p_k is taken as p_1/k, p_1 a constant, the Widrow-Hoff Rule will tend towards a solution which minimizes the squared-error in the estimate of a_k. Moreover, the CCD implementation of the Widrow-Hoff Rule need consist of only one tapped delay line with associated multipliers, summers and steering logic [18,19]. A block diagram representation of a possible CCD implementation is shown in Fig. 4.1. The multipliers summers, and logic necessary to complete the circuit could be implemented on the same substrate as the tapped delay line. The tradeoff one must make for these advantages over the multi-sample algorithm is a reduced speed of convergence. The averaging of the error gradients used in the multi-sample descent algorithm serves to "smooth" the error gradients and reduce the effect of bad data, i.e., those individual error gradients which, because of noise or other random effects, do not represent a move towards the minimum of the criterion function. The Widrow-Hoff Rule discards this averaging and thus follows a less direct path to the minimum of the criterion function. This leads to reduced speed of convergence.

4.2.4 Convergence Acceleration

Iteration speedup techniques can be used to increase the rate of convergence of the Widrow-Hoff Rule [20]. A very effective method of accelerating its convergence is to hold p_k constant as long as the error term,

$$(d^k - a_k^t D^k) \qquad (4.2.4.1)$$

maintains a constant sign. The reasoning behind this is as follows. When the search for the minimum of the error criterion is far from that minimum large steps at each iteration are desirable. As long as the sign of the error term is constant it is assumed that the search is far from the minimum, p_k is held constant and the steps stay the same size. When the error term changes sign this is an indication that the search has reached the vicinity of the sought for minimum. A smaller step size is then desirable to allow the search to converge more easily to the location of the a vector whose associated squared error is minimized. This is analogous to slowing down one's automobile so as to not pass by one's destination as it is neared.

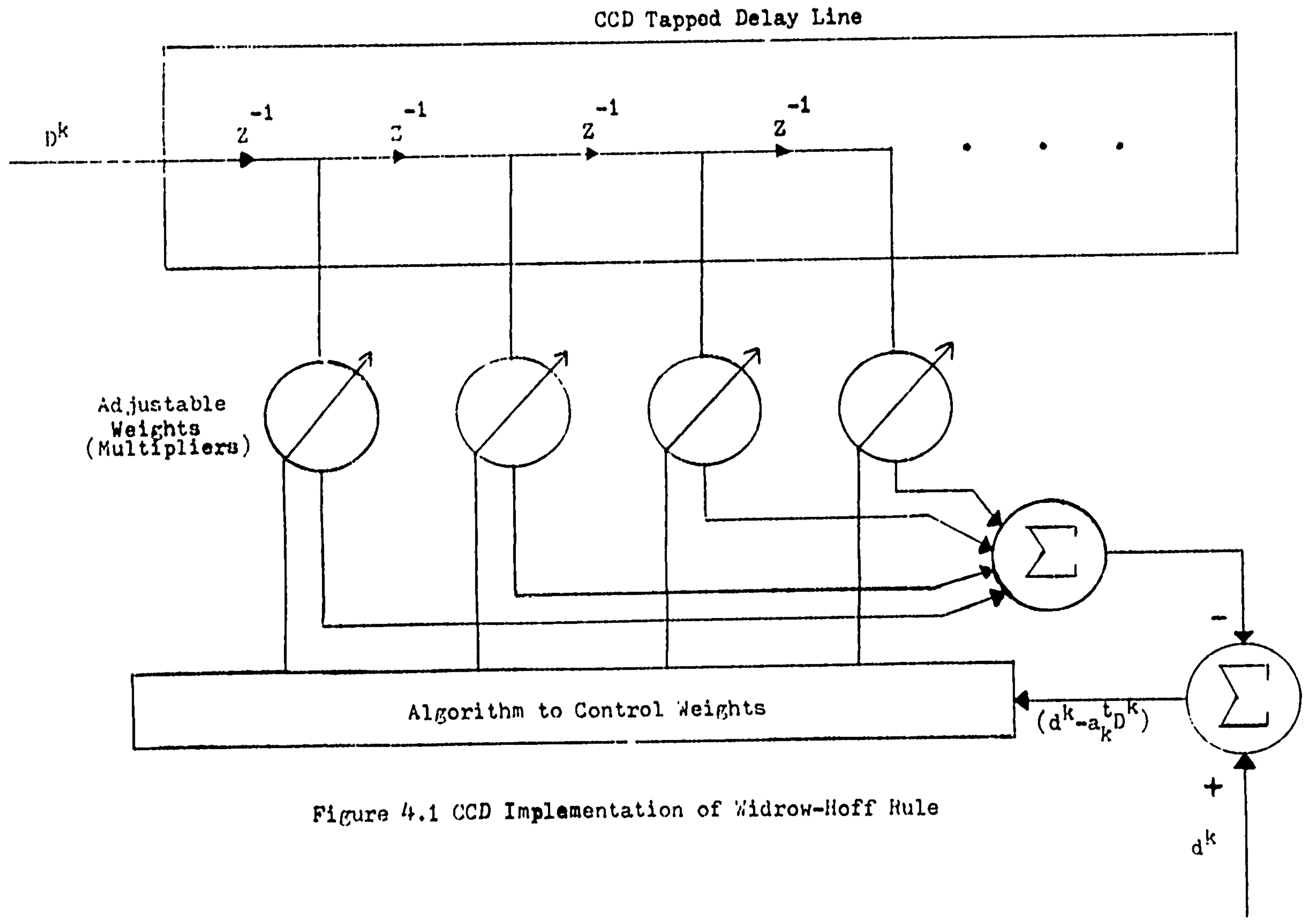


Figure 4.1 CCD Implementation of Widrow-Hoff Rule

4.2.5 Startup

The scene-to-scene temporal dependence required by the TSVIP algorithm provides another reason to be optimistic about the applicability of sequential descent algorithms to its solution. Both sequential methods presented, the multi-sample and Widrow-Hoff rules, require a starting "guess" of a_k. Without a priori information this is often chosen as 0. A more logical starting point, in this case, is simply the estimate arrived at for the previous camera frame. The assumption of fast temporal sampling required for the relevance of the TSVIP algorithm means that from frame to frame the target will appear to have a slowly changing velocity. This implies that the best "guess" for the present target movement is simply the previous estimated target movement. Using the previous target movement as the starting point for the next set of iterations provides a starting point, in the a vector space, which can be logically assumed to be near to the location which minimizes the squared-error associated with the estimate a_k. Since this allows the search to start closer to the minimum, the rate of convergence will be significantly accelerated.

4.3 Simulation

4.3.1 Introduction

A computer simulation was performed to ascertain whether the speed of convergence of the Widrow-Hoff Rule was sufficient to allow its use in implementing the TSVIP algorithm. Simulation, while not as realistic as the use of actual scene data, makes for easy confirmation of the properties of the algorithm. By varying one parameter, such as the convergence constant p_0, while holding the rest constant, the effect of each parameter on the performance of the algorithm can be determined.

The simulated scene formulation is as found in [5]. The target textural function is given as

$$f(i,j) = \frac{\sin i\Delta + 1}{i\Delta} \quad \frac{\sin(j\Delta/2.5)}{(j\Delta/2.5)} + .3j\Delta+2 \qquad (4.3.1.1)$$

where Δ, the sampling interval, is taken as .2. The target is taken as a square $16\Delta \times 16\Delta$, i.e., 16 pixels square. A flow chart of the Widrow-Hoff Rule implementation is shown in Fig. 4.2. The details of the simulated scene setup and those operations required to arrive at the linear system necessary for use of the Widrow-Hoff Rule can be found in [5].

4.3.2 Convergence Acceleration

The convergence acceleration technique used is a slight modification of the previously mentioned technique. The conventional technique is to use $p_k = p_0/k$ where p_0 is a constant and k is an integer index which is one initially and incremented by one each time the error term of the Widrow-Hoff Rule changes sign. The rationale behind this rule was previously stated. In simulation it was found that the convergence acceleration provided by this technique was not sufficient. Therefore the technique was modified by incrementing k only after a fixed number of error term sign changes, usually from three to five. It was found that very little if any further acceleration was provided beyond five sign changes. In this manner p_k did not decrease as rapidly and the step sizes, in the search for the optimum a vector, did not decrease as rapidly when compared to the step sizes produced with the conventional acceleration procedure. Through the use of this modified acceleration technique, the convergence of the Widrow-Hoff Rule could be accelerated by from 20 to 35%.

4.3.3 Size of Perturbation

The first property investigated was the effect of increasingly larger target perturbations on the accuracy and rate of convergence of the Widrow-Hoff procedure. Target movements of .05, .08, .1, and .2 were used. These represent movements of one-fourth, two-fifths, one-half, and one pixel, respectively.

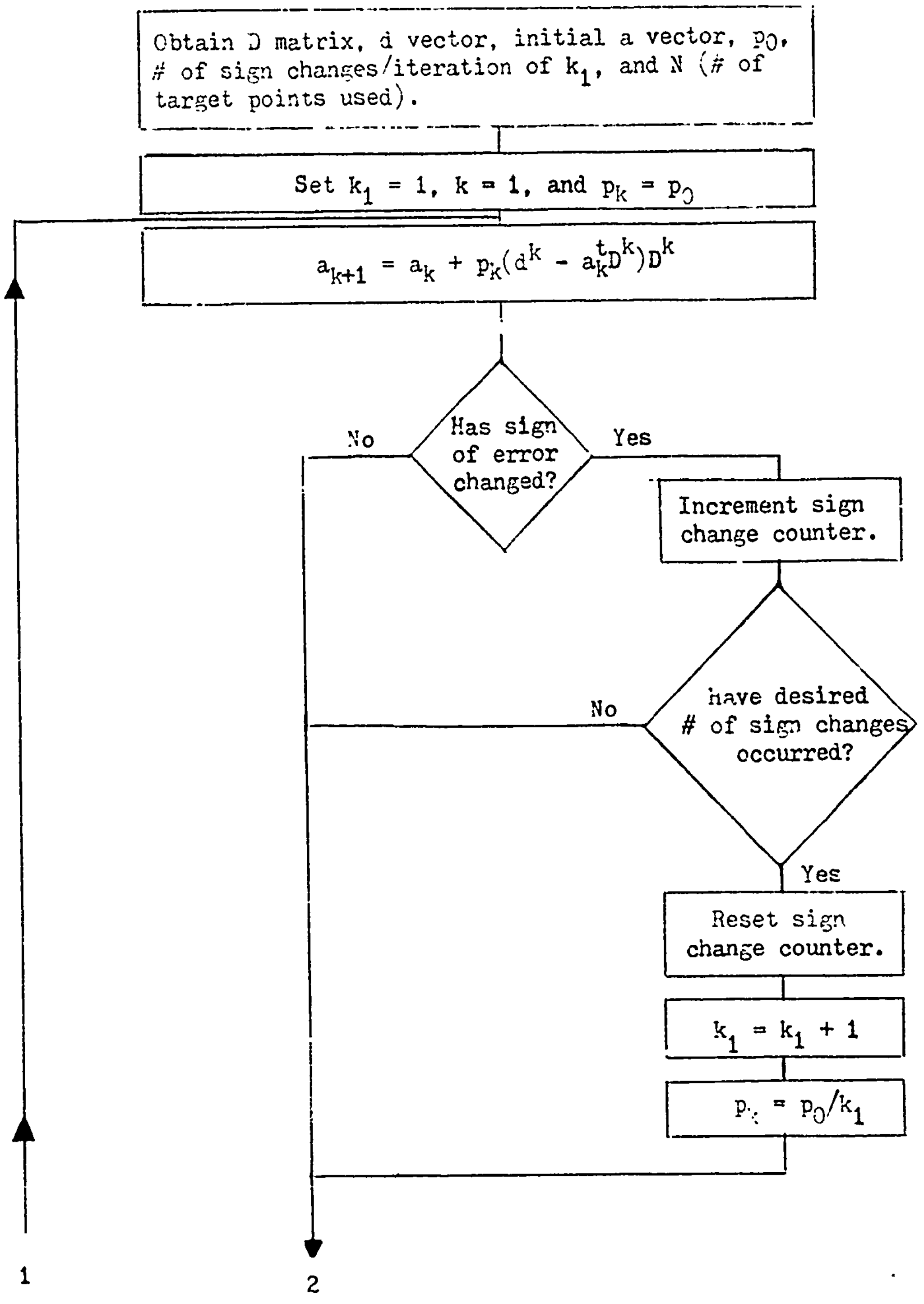

Obtain D matrix, d vector, initial a vector, p_0, # of sign changes/iteration of k_1, and N (# of target points used).
Set $k_1 = 1$, $k = 1$, and $p_k = p_0$
$a_{k+1} = a_k + p_k(d^k - a_k^tD^k)D^k$
Has sign of error changed?
No
Yes
Increment sign change counter.
have desired # of sign changes occurred?
No
Yes
Reset sign change counter.
$k_1 = k_1 + 1$
$p_k = p_0/k_1$
1
2

Figure 4.2 Flowchart of Implementation of Widrow-Hoff Rule

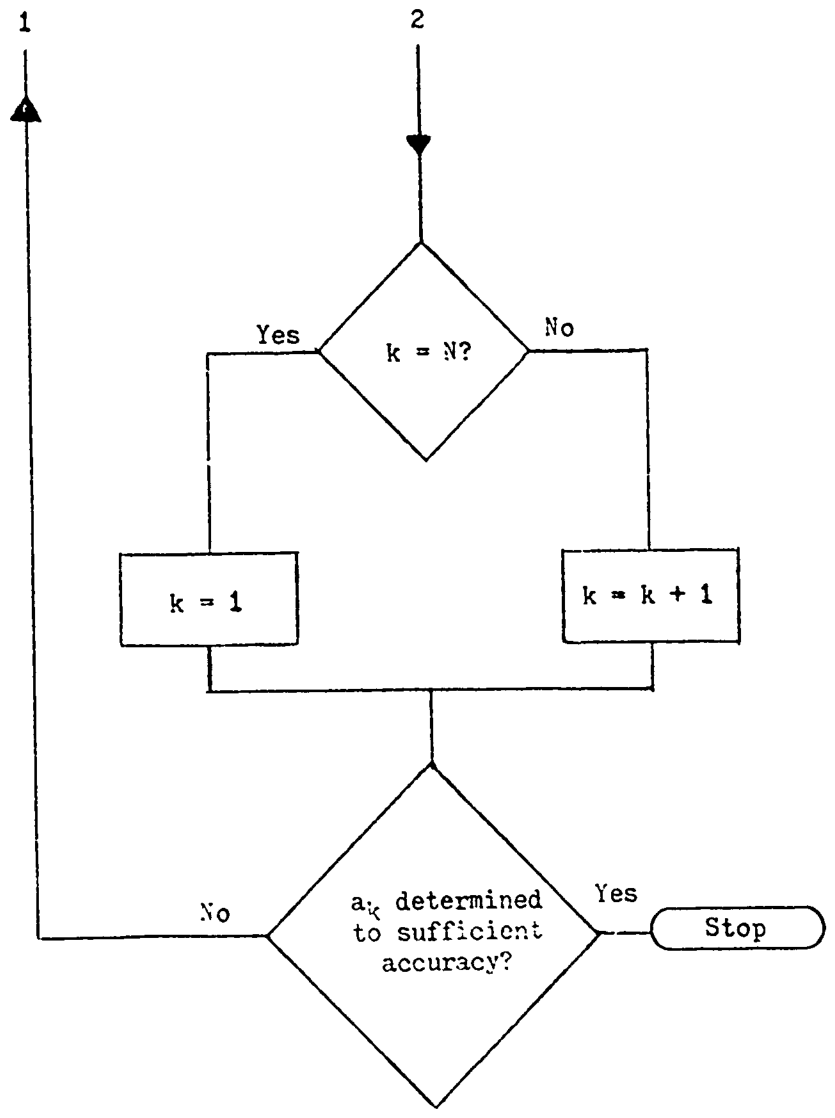


Figure 4.2 (continued)

The results of these simulated movements are summarized in Figs. 4.3-4.6. The curves with a subscript of one indicate simulations in which the starting point was selected as zero. Those curves subscripted two indicate simulations in which a starting point which was from ten to twenty percent different from the actual target perturbation was selected.

One can see at once that the Taylor series approximation begins to become invalid as the size of the target perturbation increases. While the estimate of the B(1) element of the translational vector remains accurate through the range of perturbations, the estimate of the B(2) element falls from 95% accuracy for a perturbation of .05 to 80% accuracy for a perturbation of .2. For larger target perturbations than those shown, the B(1) element also falls off in accuracy. This condition of more degradation of the B(2) element of the translational vector than of the B(1) element, for increasing target perturbation, is a function of the target textural function which is non-symmetrical in the B(1) and B(2) directions. The basic spatial frequency of the textural function in the B(2) direction is two and one-half times that in the B(1) direction. Thus, any attempt to express it in a truncated series must suffer from more truncation error than a similar expansion of the textural function in the B(1) direction.

Figures 4.3 - 4.6 also provide valuable information about the selection of the initial convergence constant p_0. In obtaining these curves, an attempt was made to use the largest p_0 possible while avoiding overshoot. Choosing p_0 too small resulted in extremely slow convergence of the algorithm. Conversely, choosing p_0 too large resulted in an oscillatory overshoot which also caused a slowing of convergence. The important finding is that the optimum p_0 increased as the target perturbation was increased. Thus, for optimum convergence p_0 cannot be chosen as a constant but must be adjusted from frame to frame.

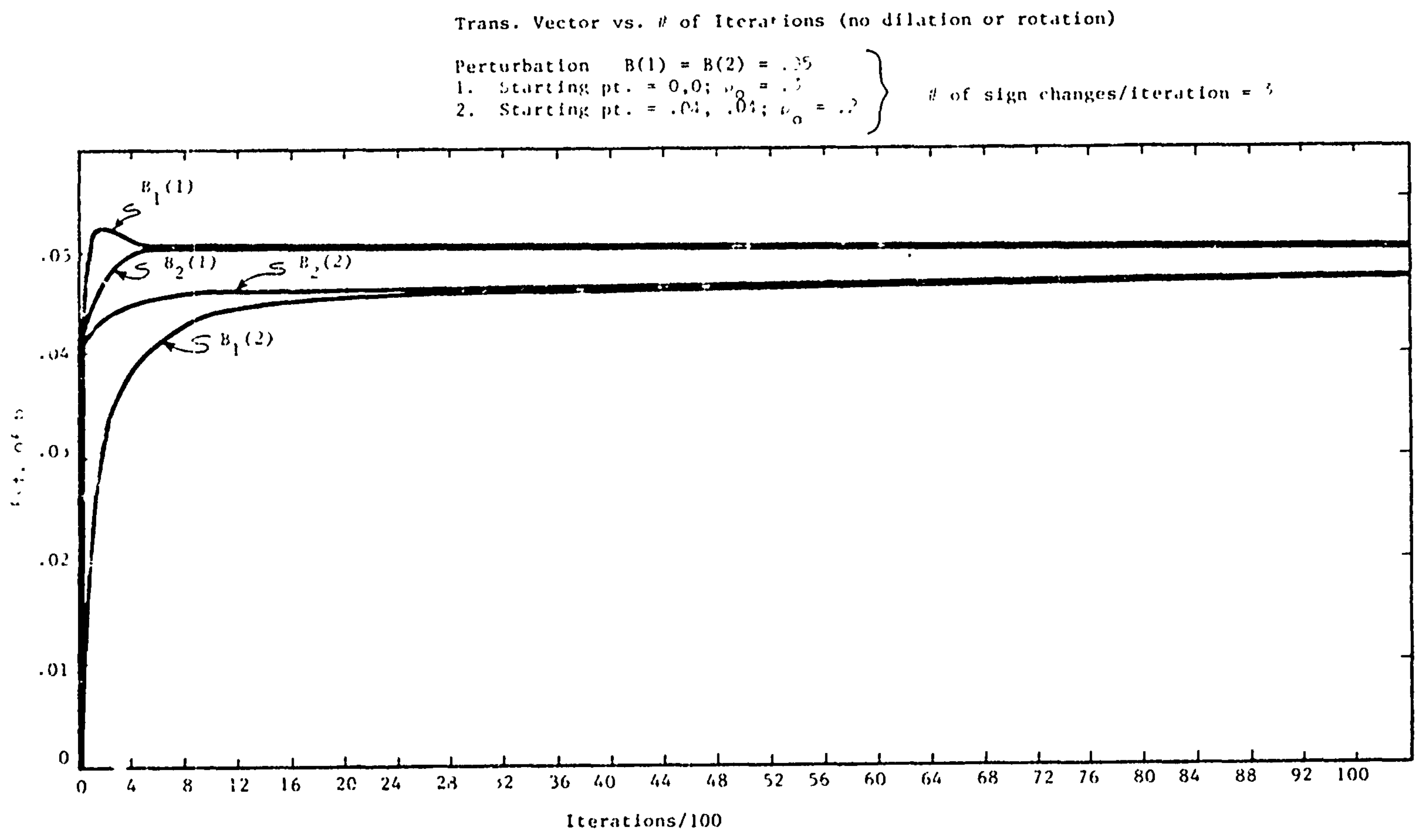

Trans. Vector vs. # of Iterations (no dilation or rotation)
Perturbation B(1) = B(2) = .35
1. Starting pt. = 0,0; ν_o = .[illegible]
2. Starting pt. = .04, .04; ν_o = .2
# of sign changes/iteration = [illegible]
$B_1(1)$
$B_2(1)$
$B_2(2)$
$B_1(2)$
.05
.04
.03
.02
.01
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
100
Iterations/100

Figure 4.3

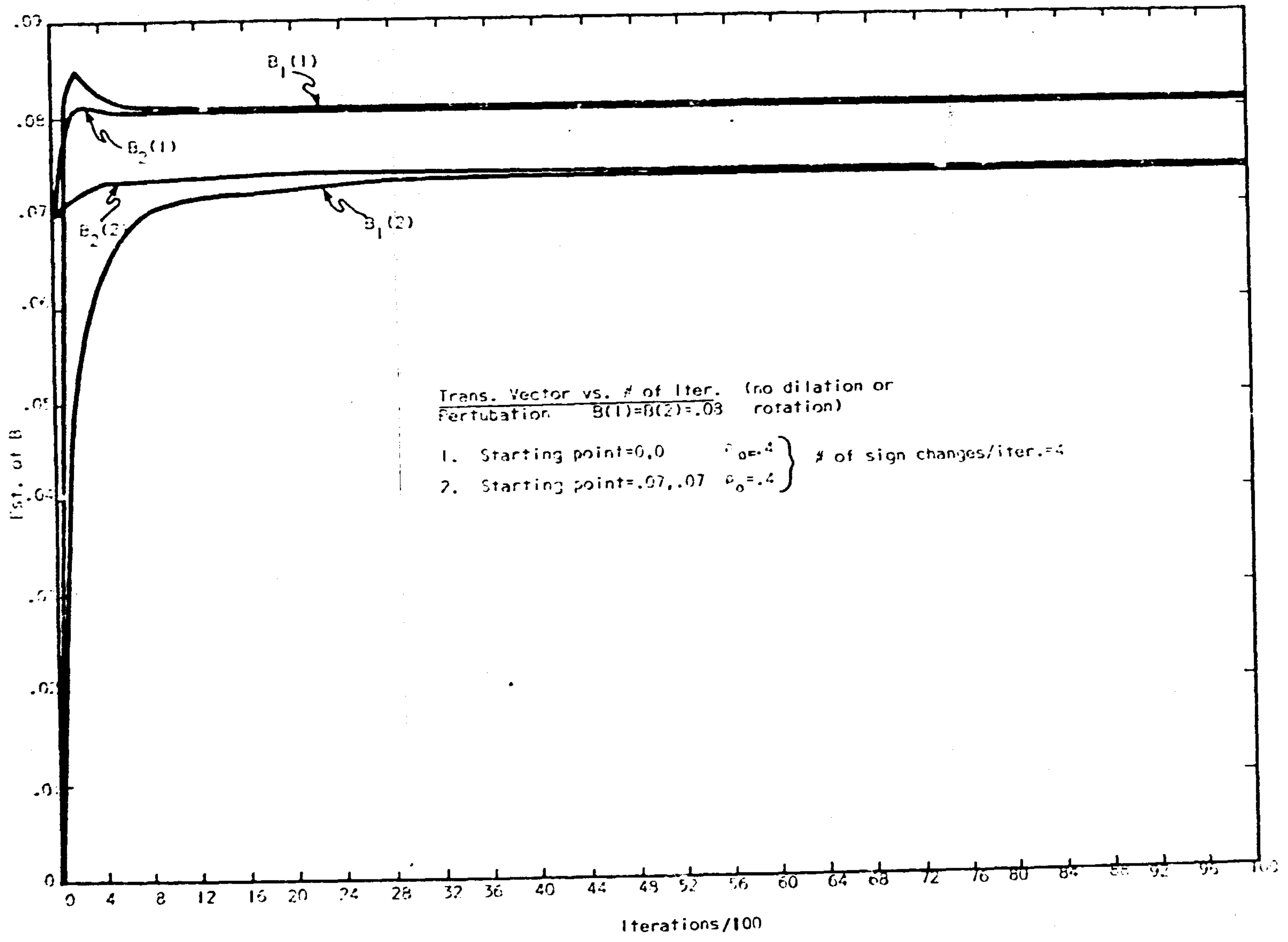

B_1(1)
B_2(1)
B_2(2)
B_1(2)
Trans. Vector vs. # of Iter. (no dilation or rotation)
Pertubation B(1)=B(2)=.08
1. Starting point=0,0 ρ_o=.4
2. Starting point=.07,.07 ρ_o=.4
# of sign changes/iter.=4
Est. of B
Iterations/100

Figure 4.4

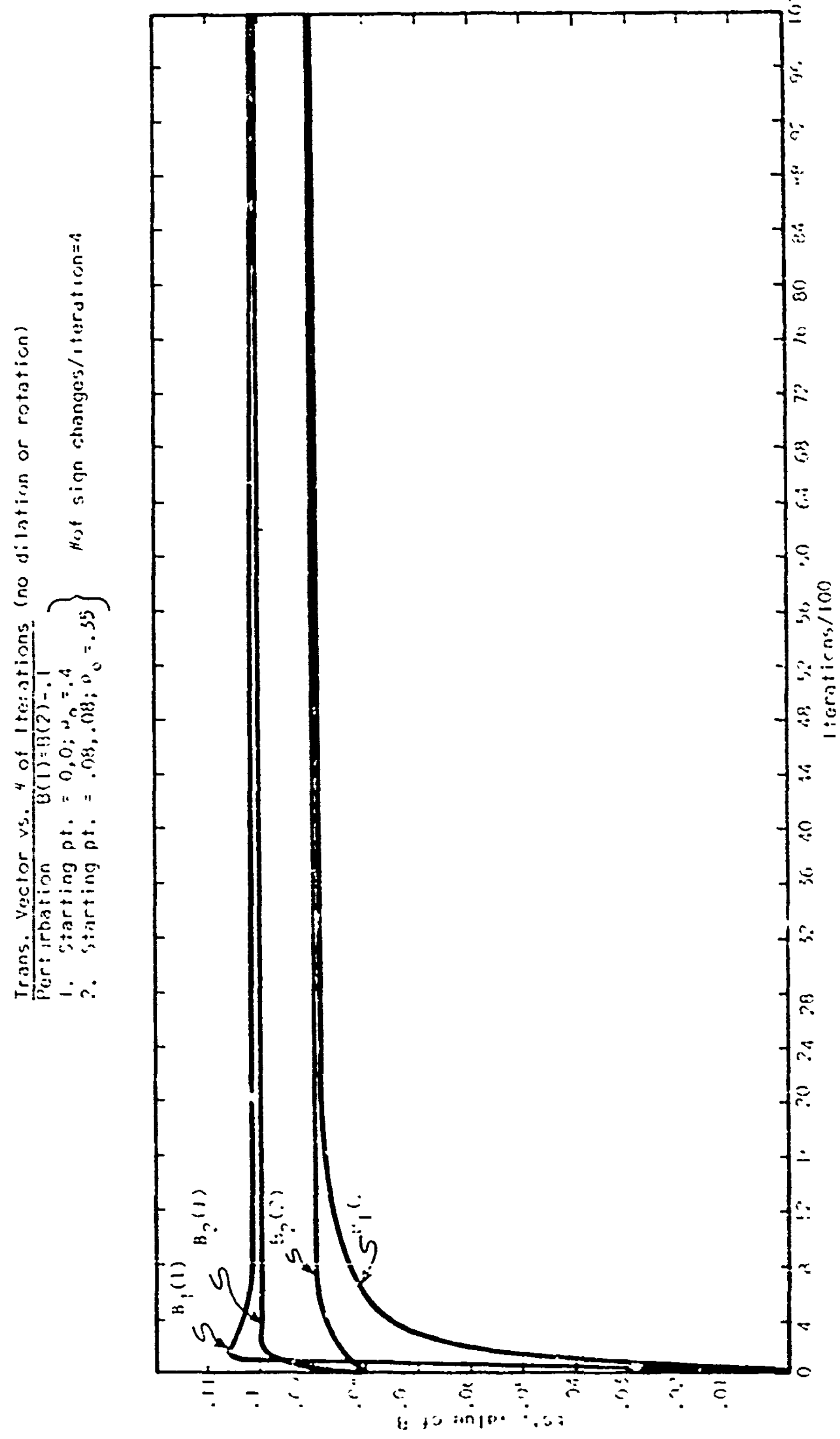

Trans. Vector vs. # of Iterations (no dilation or rotation)
Perturbation B(1)=B(2)=.1
1. Starting pt. = 0,0; ρ_0=.4
2. Starting pt. = .08,.08; ρ_0=.35
#of sign changes/iteration=4
$B_1(1)$
$B_2(1)$
$B_2(2)$
$B_1(2)$
Iterations/100
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
.11
.1
.01

Figure 4.5

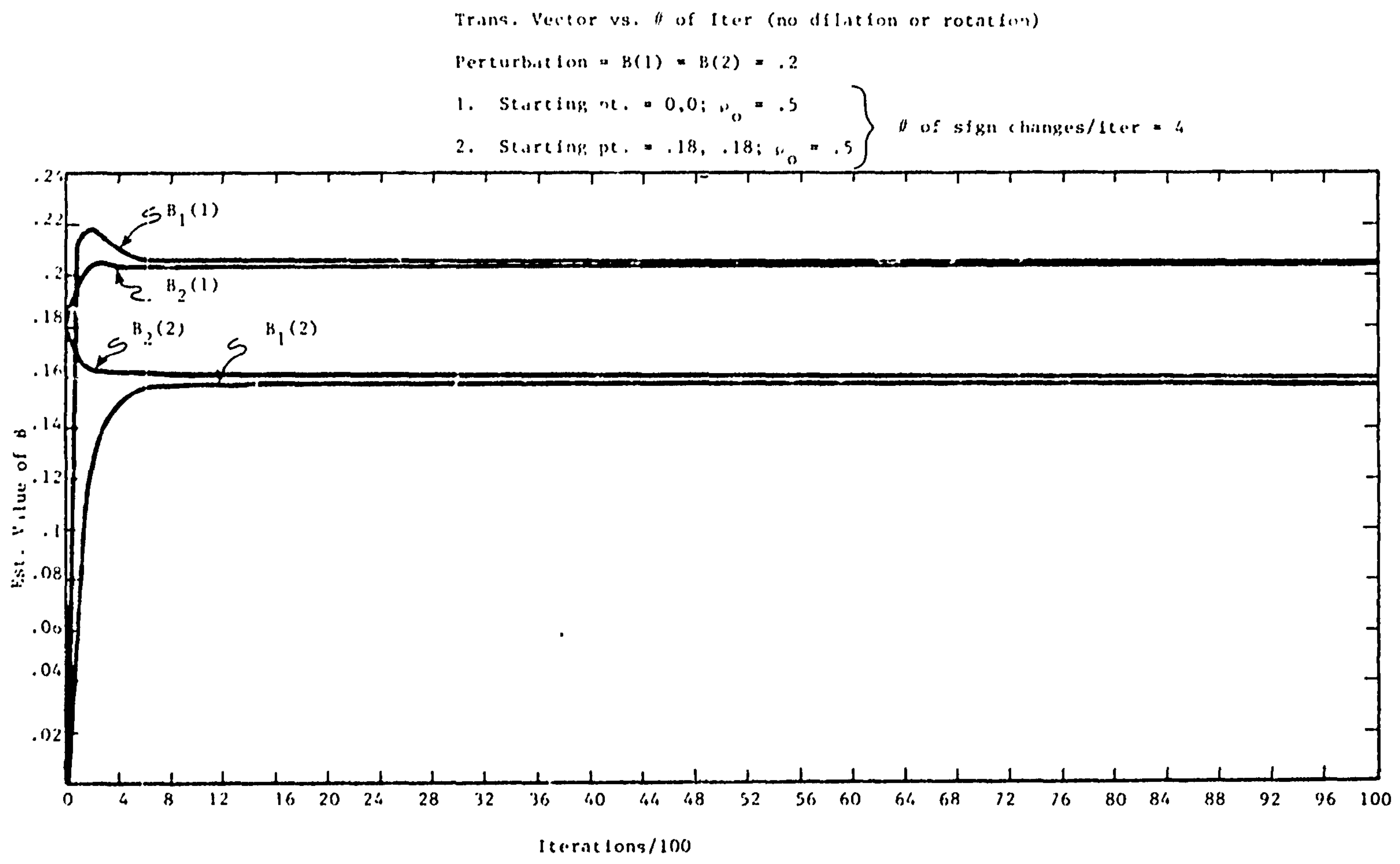

Trans. Vector vs. # of Iter (no dilation or rotation)
Perturbation = B(1) = B(2) = .2
1. Starting pt. = 0,0; ρ_o = .5
2. Starting pt. = .18, .18; ρ_o = .5
# of sign changes/iter = 4
$B_1(1)$
$B_2(1)$
$B_2(2)$
$B_1(2)$
Est. Value of B
.24
.22
.2
.18
.16
.14
.12
.1
.08
.06
.04
.02
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
Iterations/100

Figure 4.6

Since it is impossible to know a priori the magnitude of the target movement which is being estimated, the previous target movement is the best value on which to base a choice of p_0. The assumption of fast temporal sampling inherent in the TSVIP algorithm should make this a reasonable assumption. In any case the choice of p_0 should be conservative to avoid any chance of overshoot or instability in the estimation process.

For completeness, a simulation which includes target dilation and rotation is summarized in Fig. 4.7. For small perturbations the estimates of both dilation and rotation were found to be accurate and to converge quite rapidly. A more exhaustive investigation was not carried out because dilation and rotation are not of primary interest in this investigation. That is, in a tracking processor, they are of secondary interest to the target translational parameters. Additional work will be required if they are needed for control purposes.

4.3.4 Startup

As was stated in the derivation of gradient descent procedures, a starting "guess' is necessary to compute an initial error gradient. The claim was made that the previous target translation was a good candidate for this starting point as the scene-to-scene temporal dependence inherent in the TSVIP algorithm guaranteed small changes in target velocitv from frame to frame. To verify this claim the four increasingly larger target perturbations of Figs. 4.3 - 4.6 were run with starting points of from ten to twenty percent difference from the actual perturbation. The reduction in the number of iterations required for convergence ranged from 20 to 50%. The larger target perturbations benefitted more than the smaller from this choice of a startup point. The results indicate that an intelligent choice of the startup point for the Widrow-Hoff Rule can produce significant savings in the number of iterations required for convergence.

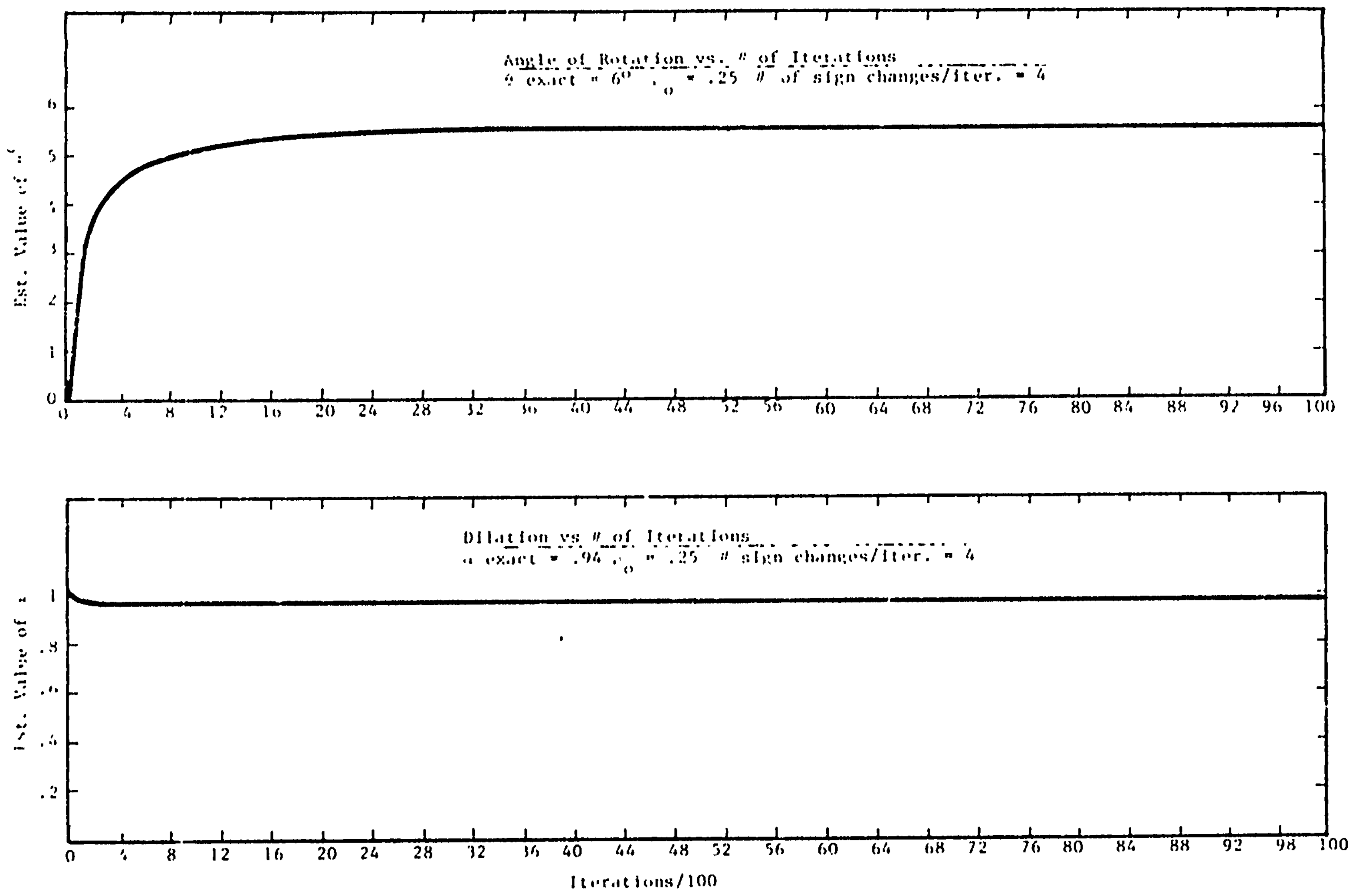

Angle of Rotation vs. # of Iterations
θ exact = 6° , λ_0 = .25 # of sign changes/iter. = 4
Est. Value of θ
0
1
2
3
4
5
6
Dilation vs # of Iterations
α exact = .94 λ_0 = .25 # sign changes/iter. = 4
Est. Value of α
.2
.4
.6
.8
1
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
Iterations/100

Figure 4.7

4.3.5 Noise Susceptibility

The previously discussed simulations were performed using exact spatial derivatives obtained from the target textural function and used no additive noise. To investigate the behavior of the Widrow-Hoff Rule in implementing the TSVIP algorithm using noise corrupted scene data the positive half of a normally distributed, zero mean noise process was added to the simulated scene. The spatial derivatives necessary to form the system of linear equations provided by the TSVIP algorithm were performed using a simple difference equation. The results are displayed in Fig. 4.8. The addition of noise to the scene produced rather unreliable estimates of the target perturbation. The estimation of spatial derivatives in a noisy environment is known to be unreliable . The error associated with additive scene noise can be attributed to this unreliability. The use of a 3 x 3 window to introduce some averaging into the spatial derivatives failed to produce any significant improvement in the results.

4.3.6 Summation

The main conclusions resulting from the preceding tracking simulations are as follows:

1. Larger target perturbations produce wors translational estimates than smaller perturbations due to the increasing truncation error inherent in a Taylor series approximation.

2. To achieve the same rate of convergence for larger target perturbations as for smaller requires an increase in p_0, the initial convergence constant.

3. An intelligent choice of the starting "guess" in the Widrow-Hoff Rule, utilizing a priori information, can significantly improve the rate of convergence.

4. The estimation of spatial derivatives in a noisy environment introduces significant error into the estimated target translational parameters provided

Trans. Vector vs. # of Iterations w/added Noise

Perturbation   B(1)=.05 (B(2), not plotted, yielded similar results

starting point= .04

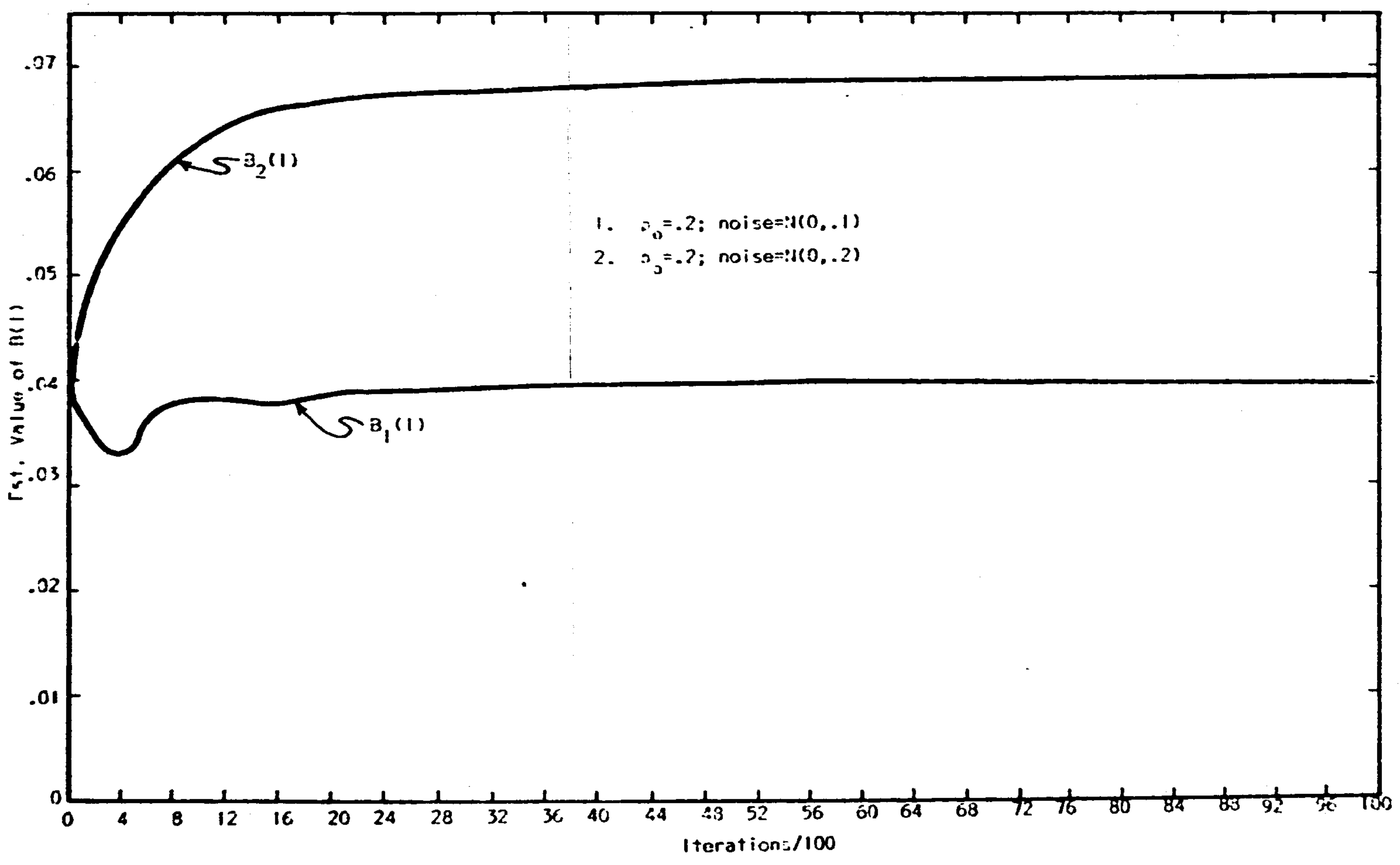


Figure 4.8

by the Widrow-Hoff Rule.

5. The results of these simulations are encouraging enough to recommend that the Widrow-Hoff Rule be tried in an implementation of the TSVIP algorithm using actual video data.

4.4 Conclusions and Recommendations for Future Study

The use of a particular sequential estimation procedure, the Widrow-Hoff Rule, has been applied to the implementation of the TSVIP tracking algorithm. For small perturbations and no additive scene noise, this estimation procedure has been shown to be effective in simulation. The use of a priori information and a slightly modified convergence acceleration procedure result in the convergence of the Widrow-Hoff Rule in an acceptably small number of iterations. The addition of noise to the simulated scene results in a significant degradation of the performance of the estimation procedure. This is a cause for some pessimism over the usefulness of the Widrow-Hoff Rule in the implementation of the TSVIP algorithm.

Future study will mainly involve obtaining actual scene data from an imaging device. It is hoped that the use of strict segmentation measures in defining target points will yield a system of linear equations which is well behaved, i.e., will yield accurate estimates when operated on by the TSVIP algorithm.

CHAPTER V

OTHER ALGORITHMS

5.1 Introduction

5.1.1 Purpose

This section reports on an investigation into the other algorithms for image tracking. Although the TSVIP algorithm appears to be the most promising, an investigation into other algorithms is necessary for several reasons. First, should the TSVIP approach prove to be ineffective, a list of possible alternatives would have been studied. Second, although the TSVIP method may work well as long as the target remains locked within the field of view, the overall system performance may require a hierarchy of algorithms which will be used in support of the TSVIP algorithm. For example, algorithms which can segment the target from the background, and ones which can locate and be used to lock the target within the field of view, may be required in some applications. Finally, alternative algorithms can serve as a basis of comparison to show how well the TSVIP algorithm performs. Thus, the general nature of this investigation is to discover image processing techniques which can either support or replace the TSVIP algorithm.

5.1.2 Constraints

There are several constraints on the algorithms that can be considered. These constraints are related to special performance and hardware requirements for the expected range of applications. The algorithms will be expected to perform in a real-time closed-loop system, and they must provide adequate lock-in and tracking performance at extremely high data rates. Thus, the algorithms themselves need to be very efficient; that is, both fast and accurate.

There are also several constraints on the type of hardware that can be implemented. The hardware will be subjected to large forces, will need to fit in small places, will probably be powered by a small power source, and will process data at a high rate. Therefore, the technology used must provide hardware that will be rugged, small, lightweight, low powered, and fast. The appropriate choice appears to be CCD based discrete analog processing, a conclusion reached in the previous algorithm work.

In CCD based image processing the analog signal is sampled at discrete intervals in time and space and processed as a discrete analog signal. As shown in a previous section, CCD devices can perform complex signal processing operations at high data rates while retaining a small size with low power consumption. But more importantly, the operations it performs are adaptive. That is, the filter transfer function can be altered in response to the data it receives. This allows a flexible and powerful hardware structure where the same basic elements can be used to perform different functions.

From the above discussion it is apparent that the algorithm search needs to be limited to those algorithms that can take advantage of CCD based structures. More explicitly, the bulk of the high speed processing should be performed with discrete analog technology implemented with CCDs, while the slower and simpler processing may use both digital and analog technologies. This hybrid of technologies will help to ensure high data processing rates, ruggedness, low power, small size, and low weight.

Constraining the hardware to be based largely on discrete analog processing unfortunately creates a constraint on the kinds of algorithms that can be investigated. There is basically one operation that is ideal for discrete analog processing, and any algorithm that can be considered in this investigation should use this operation extensively. This operation is given mathematically as

$$y(k) = \sum_{i=0}^{N-1} a(k,i)x(k-i) \qquad (5.1.2.1)$$

where $y(k)$ is the discrete analog output at time k, $x(k)$ is the discrete analog input at time k, and $a(k,i)$ is the i^{th} coefficient for the operation at time k. Notice that the output is simply a weighted sum of delayed input values. It is often referred to as a transversal filter, a moving average filter, or a finite impulse response filter.

By the appropriate choice of the time varying coefficients, this simple operation can perform a large number of functions in addition to filtering, such as estimating autocorrelations, estimating means and first order moments, estimating gradients, convolving with time variant responses, matched filtering, and discrete Fourier and other orthogonal transforms. Also by simply feeding the output back into the input a more general filtering operation is obtained. This general operation is often referred to as a recursive filter, an autoregressive filter, or an infinite impulse response filter. This basic operation as it applies to each algorithm under investigation will be developed in later sections.

In summary, the major constraint on any algorithm being investigated is that it must use this fundamental operation as the basis of its processing algorithm. This constraint will ensure fast processing, small size, low weight, low power consumption, and ruggedness.

5.1.3 Assumptions

As with any initial investigation, certain assumptions must be made about the data available at the input for processing and the type of data needed at the output to generate the appropriate control signals. Specific assumptions about the input data imposed by the nature of the target, background, and noise will be referred to in the description of individual algorithms, since these assumptions are algorithm dependent. However, there are several general assumptions that can be made about all the algorithms.

The expected range of sampling rates of the input data must be determined. The spatial sampling of any scene is dependent on the zoom capabilities of the imager and on the number of pixels in each frame. It will be assumed that each frame of the raw data will consist of an array 100 x 100 pixels in size (although this is not a limiting assumption) with no assumptions made about the zoom capabilities of the imager. Assumptions about the time sampling are needed to specify the number of frames produced every second. This is dependent on the number of pixels that the target is allowed to move from frame to frame, which in turn is dependent on the size and velocity of the target relative to the imager and on the zoom capabilities of the imager. Since this number is target dependent, it is difficult to specify. For a target 100 feet long, extending 100 pixels in the imager output array, and moving 1000 feet per second, a frame rate of 100 frames per second would allow a movement of 10 pixels per frame. This is probably a practical upper limit with a lower limit being about 1 frame per second. Note that the upper limit corresponds to a bulk pixel rate of 1,000,000 pixels per second, which is indeed a very high data rate, but one which can be handled easily by CCDs.

The output control signals are used to keep the target within the field of view. With this feedback, the system will be expected to track a specified target. There are two approaches to deriving a set of tracking parameters. One approach is based on relative positional measurements, while the other approach is based on absolute positional measurements. The relative approach gives parameters which indicate changes in target position, size, and angle of orientation relative to some previous estimate. The absolute approach gives parameters that specify target position, size, and angle of orientation in reference to a fixed system. The TSVIP approach is a relative one, since it gives frame to frame differences in x and y positions, differences in angle of orientation, and ratios of size changes. Note that each parameter set can be estimated from the other one, once a common reference position is established. Also note that the relative approach may allow errors in the positional estimate to accumulate, since these errors are fed back into the input of the system, while in the absolute approach these errors are not fed back. Which approach is used will be specified in the discussion of the individual algorithms in the following sections.

5.2 The Algorithms

In this section several feasible algorithms for performing image tracking are introduced. The discussion of each algorithm includes its underlying principles and the assumptions it makes about the input data. The five categories of the algorithms being investigated are referred to as gradient, moment, coordinate, transformation, and segmentation.

5.2.1 Gradient Algorithms

5.2.1.1 Development

These algorithms include the TSVIP algorithm discussed earlier in this report and Lie theoretical methods [21]. The fundamental equation of these algorithms can be developed mathematically either in terms of a Taylor series expansion of the equation governing motion of a target or in terms of group theoretic methods, but since this development is complex and can be referenced elsewhere [5,21,22], only the results are presented here.

In theory the fundamental relation equates the time derivative of the image intensity at a point as a nonlinear function of the coordinates of the point and the spatial derivatives at that point, and is given from the Lie formulation as

$$\partial f/\partial t = a_{11}x(\partial f/\partial x)+a_{12}y(\partial f/\partial x)+a_{21}x(\partial f/\partial y)+a_{22}y(\partial f/\partial y)+b_1(\partial f/\partial x)+b_2(\partial f/\partial y) \tag{5.2.1.1}$$

where $f=f(x,y,t)$ is the image intensity as a function of the x-y image plane and time. At any given time, the six coefficients (a_{11},a_{12},a_{21},a_{22},b_1, and b_2) are assumed constant over all points within the target. Thus, an overconstrained set of N linear equations (where $N > 6$) in six unknowns can be derived by estimating the derivatives at N points within the target at a given point in time. These equations can then be solved for the six unknowns with any of a large number of descent procedures [16,20] that can be implemented with CCDs. Two possible solutions, the least squares pseudoinverse solution and the Widrow-Hoff sequential deterministic solution, are developed in Chapter IV of this report. One other CCD implementable solution, a Kalman filter formulation of the estimation problem, is proposed in this chapter. Since two other algorithm groups, moment and coordinate, also produce an overconstrained set of linear equations and can be solved with the same procedures, the Kalman procedure is presented in Section 5.2.4 after discussion of these algorithms.

It is interesting to compare the Lie formulation given by (5.2.1.1) with the TSVIP formulation. Even though the two equations are developed from quite different formulations, they are very similar. The only difference is that the TSVIP algorithm approximates the time derivative of the intensity function with the difference between two consecutive frames,

$$\partial f(x,y,t)/\partial t \overset{\sim}{=} f(x,y,t+T)-f(x,y,t) \tag{5.2.1.2}$$

There is an interesting physical interpretation of the coefficients derived in these formulas, when the coefficients are constrained such that $a_{11} = a_{22} = a_1$ and $-a_{12} = a_{21} = a_2$. This constraint restricts target motion to translation, rotation, and dilation. If the target is rotating in the image plane at a rate $d\theta/dt$ about some point (x_o,y_o) and expanding at the rate of $d\rho/dt$ about this same point, which is moving with rectangular velocity components given by dx/dt and dy/dt, then the constrained parameters give the following relationships:

$$d\theta/dt = \tan^{-1}(a_2/a_1) \tag{5.2.1.3a}$$

$$1+(1/\rho)d\rho/dt = \sqrt{a_1^2 + a_2^2} \tag{5.2.1.3b}$$

$$dx/dt = b_1 \tag{5.2.1.3c}$$

and

$$dy/dt = b_2 \tag{5.2.1.3d}$$

If for some small time interval, T, these derivatives ($d\theta/dt$, $d\rho/dt$, dx/dt, and dy/dt) can be assumed constant, then a constrained Affine transformation of coordinates can be given by

$$\begin{bmatrix} x(t+T) \\ y(t+T) \end{bmatrix} = \begin{bmatrix} a_1 & -a_2 \\ a_2 & a_1 \end{bmatrix} \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \tag{5.2.1.4}$$

where

$$a_1 = [\rho(t+T)/\rho(t)]\cos[\theta(t+T)-\theta(t)]$$

$$a_2 = [\rho(t+T)/\rho(t)]\sin[\theta(t+T)-\theta(t)]$$

$$b_1 = x_o(t+T)-x_o(t)$$

and

$$b_2 = y_o(t+T)-y_o(t)$$

Thus, a relativistic set of parameters about changes in target orientation, position, and size between consecutive frames can be generated as:

$$\Delta x = b_1 \tag{5.2.1.5a}$$

$$\Delta y = b_2 \tag{5.2.1.5b}$$

$$\Delta\theta = \tan^{-1} (a_2/a_1) \tag{5.2.1.5c}$$

and

$$\alpha = \sqrt{a_1^2 + a_2^2} \tag{5.2.1.5d}$$

5.2.1.2 Assumptions

There are several major assumptions made by gradient algorithms about the type of data available for processing. One important assumption is that the target has been roughly segmented in some way from the background, so that a set of known target points exists for processing. Also the target must be large enough so that a sufficient number of sampling points exist. Note that no assumptions are necessary for the background points. In fact a background is not even required, unless it is needed for segmentation.

Another important assumption is that the spatial and time derivatives at a point can be easily estimated from the sampled intensity values at that point and its surrounding points. This implies that the spatial and time sampling rates must be high enough for good estimates, but not so high that the equations are ill-conditioned. This requirement also relates to the texture and motion of the target in that variations in image intensity values from sampled point to sampled point can neither be too large nor too small. Also since derivative estimates are very sensitive to noise, the noise levels need to be low. This can be achieved to some degree by low pass filtering the input data before the derivative estimates are made.

A third assumption is that an additional algorithm is being used to provide absolute estimates of the target position. This is necessary since relative estimates can accumulate error and, without an additional algorithm, can lose track of the target.

The final assumption is that the target is restricted to motion as given by the unconstrained Affine transform. Since most physical motions will tend to be ones of this type, this assumption is not too critical.

5.2.2 Moment Algorithms

5.2.2.1 Development

These algorithms are based on means and moments of the input data as opposed to gradients. They perform an averaging of the data, and thus are less sensitive to noise and sampling rates than gradient based algorithms. However, they are very similar to the gradient algorithms in that they establish a fundamental equation at each point in a target describing its spatial and time perturbations. This fundamental equation is based on the same six unknowns and is derived from the fundamental gradient equation by a spatial integration of it. The integration is carried over a fixed area centered on a target point. If the area is defined by $a \le x \le b$ and $c \le y \le d$, then the integration operation on the fundamental gradient equation yields:

$$\begin{aligned}\int_c^d \int_a^b (\partial f/\partial t)\,dx\,dy &= a_{11} \int_c^d \int_a^b x(\partial f/\partial x)\,dx\,dy + a_{12} \int_c^d \int_a^b y(\partial f/\partial x)\,dx\,dy \\ &+ b_1 \int_c^d \int_a^b (\partial f/\partial x)\,dx\,dy + a_{22} \int_a^b \int_c^d y(\partial f/\partial y)\,dy\,dx \\ &+ a_{21} \int_a^b \int_c^d x(\partial f/\partial y)\,dy\,dx + b_2 \int_a^b \int_c^d (\partial f/\partial y)\,dy\,dx\end{aligned} \quad (5.2.2.1)$$

This equation can be further reduced by noting the following equalities of calculus:

$$\int_c^d \int_a^b [\partial f(x,y,t)/\partial t]dx\, dy = \partial V(t)/\partial t \qquad (5.2.2.2a)$$

$$\int_c^d \int_a^b x[\partial f(x,y,t)/\partial x]dx\, dy = b\int_c^d f(b,y,t)dy - a\int_c^d f(a,y,t)dy - V(t) \qquad (5.2.2.2b)$$

$$\int_a^b \int_c^d y[\partial f(x,y,t)/\partial y]dy\, dx = d\int_a^b f(x,d,t)dx - c\int_a^b f(x,c,t)dx - V(t) \qquad (5.2.2.2c)$$

$$\int_c^d \int_a^b y[\partial f(x,y,t)/\partial x]dx\, dy = \int_c^d yf(b,y,t)dy - \int_c^d yf(a,y,t)dy \qquad (5.2.2.2d)$$

$$\int_a^b \int_c^d x[\partial f(x,y,t)/\partial y]dy\, dx = \int_a^b xf(x,d,t)dx - \int_a^b xf(x,c,t)dx \qquad (5.2.2.2e)$$

$$\int_c^d \int_a^b [\partial f(x,y,t)/\partial x]dx\, dy = \int_c^d f(b,y,t)dy - \int_c^d f(a,y,t)dy \qquad (5.2.2.2f)$$

$$\int_a^b \int_c^c [\partial f(x,y,t)/\partial y]dy\, dx = \int_a^b f(x,d,t)dx - \int_a^b f(x,c,t)dx \qquad (5.2.2.2g)$$

where

$$V(t) = \int_c^d \int_a^b f(x,y,t)dx\, dy$$

Note that this reduction eliminates all but one derivative operation, and replaces them with zero and first order moment calculations of the windowed area and its boundaries. Again the single time derivative operation in (5.2.2.2a) can be replaced by

$$\partial V(t)/\partial t \simeq V(t+T)-V(t) \qquad (5.2.2.3)$$

as long as the time sampling rate is fast enough or the image evolves slow enough to make this approximation valid.

Since the data are discrete, the integral operations must also be approximated by some numerical integration technique. The simplest and most easily implementable with CCDs is the rectangular rule:

$$\int_a^b g(x)dx = \sum_{n=0}^{N-1} g(a+n\Delta x)\Delta x \qquad (5.2.2.4)$$

where $\Delta x = (b-a)/N$. Thus, all the integration operations in (5.2.2.2) can be developed as weighted sums of ordered pixels and thereby be implemented with CCD based structures.

Since the coefficients are identical in the two formulations, they have the same interpretation as given by (5.2.1.3), and they generate the same relative set of control signals as given by (5.2.1.5). Also they can be calculated using the pseudo-inverse formulation or the Widrow-Hoff formulation as presented earlier in this report, or using the Kalman formulation presented in Section 5.2.4.

5.2.2.2 Assumptions

With few exceptions the assumptions made by these algorithms are essentially identical to those made by the gradient based algorithms as presented in Section 5.2.1.2. However these algorithms do not require special constraints on the spatial sampling rate or the texture of the object, nor do they require a low noise level as in the gradient algorithms.

5.2.3 Coordinate Algorithms

5.2.3.1 Derivation

The coordinate based algorithms also produce an overdetermined set of linear equations as do the gradient and moment algorithms, but they do not require the estimation of either the gradient at any point or the moment of any region. They do however require the accurate identification of the locations of a fixed number of points in consecutive frames. If a subset of N points from the target can be accurately tracked in each frame, then the target as a whole can also be tracked. Labelling these N points as

$(x_1(t), y_1(t)), (x_2(t), y_2(t)), \ldots, (x_N(t), y_N(t))$, the linear set of equations become

$$\begin{aligned}
x_1(t+T) &= b_1 + a_{11}x_1(t) + a_{12}y_1(t) \\
y_1(t+T) &= b_2 + a_{21}x_1(t) + a_{22}y_1(t) \\
x_2(t+T) &= b_1 + a_{11}x_2(t) + a_{12}y_2(t) \\
y_2(t+T) &= b_2 + a_{21}x_2(t) + a_{22}y_2(t) \\
&\vdots \\
x_N(t+T) &= b_1 + a_{11}x_N(t) + a_{12}y_N(t) \\
y_N(t+T) &= b_2 + a_{21}x_N(t) + a_{22}y_N(t) \qquad (5.2.3.1)
\end{aligned}$$

The coefficients correspond to those of the unconstrained Affine transformation as given in (5.2.1.1) or (5.2.2.1), and thus have the same physical interpretation and output the same control signals as both the gradient and moment algorithms. They can also be solved using the same methods.

The major difference is that accurate segmentation of a few points is required. If that can be done, and since this formulation does not need the image intensity value at any point, both noise problems and spatial and time sampling constraints can be ignored. Since noise does not work into the equations, a more accurate solution can be obtained. Unfortunately, the task of tracking a select set of image points is very target dependent and may be too difficult to implement with any reasonable algorithm or hardware.

5.2.3.2 Assumptions

The coordinate based algorithms have only two major assumptions. The first and most prohibitive is that accurate positional identification of a select set of points is required in successive frames. This assumes that the target consists of identifiable points such as the intersections of edges or boundaries, points that are consistently the largest or smallest values from scene to scene, or points that come from matched filtering with regions of known size and shape. It is this assumption that may prohibit coordinate based algorithms from being implementable.

Another assumption is that target motion is restricted to those allowed by the unconstrained Affine transform. Motions such as translation, dilation, and rotation within the x-y viewing plane are nicely modeled by the Affine parameters, but rotations about an axis that is not orthogonal to the viewing plane are not. Even so, this restriction is essentially a mild one.

5.2.4 A Kalman Based Solution of the Affine Parameters

In this section a solution technique for solving an overdetermined set of equations in six unknowns is presented. This technique applies to the gradient, moment, and coordinate generated equations. In fact, since the coefficients are identical in all three approaches, a novel idea might be to use N gradient derived equations, M moment derived equations, and P coordinate derived equations as the input data for either this Kalman technique or any of the others discussed in this paper. Care should be taken, however, so that the data from all three sources are about the same order of magnitude, else the equations would be ill-conditioned. Normalization can be easily handled by adjusting the CCD tap weights as this data is computed.

The development of this technique is presented in vector form, so let

$$A^T(k) = [a_{11}(k)\ a_{12}(k)\ a_{21}(k)\ a_{22}(k)\ b_1(k)\ b_2(k)] \qquad (5.2.4.1a)$$

and

$$X^T(k) = [x_1(k)\ x_2(k)\ x_3(k)\ x_4(k)\ x_5(k)\ x_6(k)] \qquad (5.2.4.1b)$$

where k is the iteration index, A(k) represents the sequential estimates of the unconstrained Affine parameters, and $X^T(k)$ represents the kth data set derived either by gradient, moment, or coordinate calculations. The elements of $X^T(k)$ represent the data weights on the corresponding coefficients in A(k) so that the kth derived equation from any of the techniques is represented by

$$Z(k) = A^T(k)X(k) \tag{5.2.4.2}$$

where Z(k) is the left side quantity as given in (5.2.1.1),(5.2.2.1), or (5.2.3.1).

Since the Affine parameters are assumed constant over all observations in a particular frame, A(k) can be modeled as the following Markov process:

$$A(k+1) = A(k) + u(k) \tag{5.2.4.3}$$

where u(k) is modeled as a stationary white noise process with variance V_u, thus allowing for the error in the parameter estimates from different observations. The observation equation can then be given as

$$Z(k) = A^T(k)X(k) + v(k) \tag{5.2.4.4}$$

where v(k) is modeled as a stationary white noise process with variance V_v. Assume that A(0) is a random vector with variance $V_A(0)$.

Finally the estimation equations come directly from applying the above equations to Kalman filter theory, and are given as

$$A(k+1) = A(k) + \rho(k)X(k)[Z(k) - A^T(k)X(k)] \tag{5.2.4.5a}$$

$$\rho(k) = V_A(k)/[V_v^2 + X^T(k)V_A(k)X(k)] \tag{5.2.4.5b}$$

and

$$V_A(k+1) = [I - \rho(k)X(k)X^T(k)]V_A(k) + V_u \tag{5.2.4.5c}$$

Thus, all that is needed to start the sequence of estimation is to choose V_u, V_v, A(0), and $V_A(0)$. The rate of convergence is influenced by both V_u and V_v.

If V_v is chosen to be small, then from (5.2.4.5c) the product $(\rho(k)X(k)X^T(k))$ is nearly equal to the identity matrix and $V_A(k)$ will converge to its minimum value V_u too quickly. Conversely if V_v is chosen to be large, $V_A(k)$ will tend to V_u very slowly. The choices for $A(0)$ and $V_A(0)$ are interdependent, in that $V_A(0)$ should be chosen small if the initial estimate $A(0)$ is thought to be accurate or $V_A(0)$ should be chosen large if the estimate is believed to be inaccurate. Note that the estimates should vary little from frame to frame, so that if the estimate from the previous frame is used for $A(0)$, then $V_A(0)$, V_v, and V_u should be chosen small for quick convergence to an accurate solution. A few startup frames should be sufficient to accurately choose $A(0)$.

Implementation of this technique is more difficult than the Widrow-Hoff technique, but note the estimation similarities. The major difference is that the gain on the error term is a 6 x 6 matrix in this formulation, and it is a scalar in the Widrow-Hoff formulation. In spite of the higher complexity, the Kalman formulation is still CCD implementable since it does not require any large inverses but rather parallel computation of inner products. Also the increase in hardware over the Widrow-Hoff estimator may be an acceptable trade-off for the decrease in convergence time offered by the Kalman estimator.

5.2.5 <u>Transformation Algorithms</u>

5.2.5.1 <u>Derivation</u>

The basic principle behind these algorithms is to transform the image input data into a new set of data where the computations of rotational, translational, and dilational parameters are made easier. This section investigates some of the properties of the Fourier transform and a geometric coordinate transform denoted as the Log-Polar transform. The function of each of these transforms in computing certain motion parameters is then discussed.

The spatial Fourier transform of an image f(x,y,t) is given by

$$F(u,v,t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y,t)\exp[-2\pi j(ux+vy)]dx\,dy \qquad (5.2.5.1)$$

The following properties show the effects that translation, dilation, and rotation of an image f(x,y,t) has upon its Fourier transform. If $f(x,y,t)\leftrightarrow F(u,v,t)$ indicates the Fourier pair, then

$$f(x-x_o,\ y-y_o,\ t)\leftrightarrow \exp[-2\pi j(ux_o + vy_o)]F(u,v,t) \qquad (5.2.5.2a)$$

$$f(ax,ay,t)\leftrightarrow (1/a)^2[F(u/a,v/a)] \qquad (5.2.5.2b)$$

and

$$f(r,\ \theta+\theta_o)\leftrightarrow F(w,\phi+\theta_o) \qquad (5.2.5.2c)$$

where $f(r,\theta+\theta_o)$ represents a θ_o rotation of the image about the origin. There are three important results of the above properties. The first is that the magnitude of the Fourier transform is invariant to translation. The second is that scaling the image function also scales the Fourier transform. And lastly, a rotation about the origin in the image plane results in a rotation about the origin of the same amount in the Fourier transform plane.

The Log-Polar transform is based on the conversion from rectangular to polar coordinates and is given as

$$L(u,v,t) = f[\ln(x^2+ y^2)^{\frac{1}{2}},\ \tan^{-1}(y/x)] \qquad (5.2.5.3)$$

Basically, the image function is converted to polar coordinates, the natural logarithm is applied to its magnitude coordinate, and the new coordinate system is interpreted as rectangular coordinates. If $f(x,y,t) \rightarrow L(u,v,t)$ represents this transformation then the following properties result:

$$f(ax,ay,t) \rightarrow L(u + \ln(a),v,t) \tag{5.2.5.4a}$$

and

$$f(r,\theta+\theta_o) \rightarrow L(u,v + \theta_o,t) \tag{5.2.5.4b}$$

where $f(r,\theta+\theta_o)$ represents a θ_o rotation of the image about the origin. Note that this transformation produces a simple translation in the transformed domain given a rotation and dilation in the image domain. Also, using the translation invariance of the magnitude of the Fourier transform, a transformation of the image function that is invariant to translation, rotation, and dilation can be obtained. This is done by computing the magnitude of the Fourier transform of the Log-Polar transform of the magnitude of the Fourier transform of the original data. This invariant transform is useful in pattern recognition problems by characterizing objects subject to rotation, dilation, and translation. If the imager loses track of the target, a pattern recognition routine can take over to match the last frame containing the target with a new frame zoomed back to show a much larger image plane, and this transform can be used to locate the missing target.

A transform of the image plane which is invariant to translation, rotation, and dilation is certainly useful, but doesn't yield the parameters that indicate the amount of movement. To do this using these transforms, matched filtering is required. The actual procedure that must be performed is too complex to detail in this report, so only a brief description of this procedure is outlined.

Matched filtering is essentially a normalized cross-correlation between a function and a reference function. In this application, a windowed region containing part of the target of a previous frame is used as a reference function and is matched filtered with the current frame where the target has undergone only translation. The matched filter produces an image that has a value at the location where the target has shifted to. Unfortunately the target is only allowed to undergo translation.

If the target undergoes translation, rotation, and dilation, then the rotation and dilation parameters can be found by match filtering the Log-Polar transform of the magnitude of the Fourier transform of the reference plane with a similar transformation of the current plane. The peak value in the match filter output indicates the amount of rotation and dilation.

Once these coefficients are found, they can be applied to the current image to correct for any rotation and dilation of the reference image. The result can then be inverse Fourier transformed and match filtered with the reference image. The peak now indicates the translation movements since the reference image.

The number of computations that must be performed to derive the movement parameters is enormous. However, many of the necessary operations can take advantage of the high speed and parallel processing nature of CCDs. The Fourier transform is implemented with the discrete Fourier transform which has a CCD implementable form. Also match filtering is simply convolution with a spatially reversed reference, and CCDs can be structured to handle two dimensional convolutions. Operations such as tangents, logarithms, magnitudes, and squaring can be implemented with special purpose high speed analog or digital hardware.

5.2.5.2 Assumptions

There are several assumptions made by this procedure for identifying the tracking parameters. The foremost one is that this algorithm allows only translation, dilation, and rotation. Noise and rotation about an axis not perpendicular to the viewing plane are not accounted for, and thus will cause errors in the parameters that are measured. Another assumption is that the noise must either be low level or stationary and white, since the match filter is optimum only in the presence of white noise. Finally, unlike the previous algorithms, large changes in position, size, and orientation are all allowed by this algorithm, and so no assumptions about the time sampling rate need to be made.

5.2.6 Segmentation Algorithms

The purpose of these algorithms is to segment the target from the background and then use this segmented image to estimate the target size, position, and orientation. There are two computational parts to these algorithms: Segmentation and parameter estimation. Three segmentation methods denoted by intensity methods, texture methods, and Gestalt methods are suggested. Two parameter estimation methods denoted by principal axis methods and projection methods are proposed.

5.2.6.1 Intensity Segmentation

These methods assume that the gray levels belonging to the target pixels are significantly different from those of the background. In this case segmentation can be achieved by thresholding with the appropriate thresholds. The difficulty lies in the determination of these thresholds. If some a priori knowledge is available about the distribution of target and background intensity values is available, then a Bayesian criterion can be used to determine the optimum thresholds. If not, then a histogram of the image can be computed and the intensity levels belonging to the target can be identified if only the shape of the target distribution is known. Another possibility would be to apply the above methods to either a low-pass, high-pass, or band-pass version of the image. The filtered image may have target pixels whose intensity are distinct from those of the background.

The exact method used for intensity segmentation is highly dependent on the assumptions made about the target. Since the expected range of applications is large, no assumptions will be presented in this investigation. Only possible procedures are suggested.

5.2.6.2 Texture Segmentation

These algorithms assume that the texture of the target is significantly different from that of the background. Texture, however, is a subjective quality. One means of giving texture a quantitative measure comes from linear prediction theory. Linear prediction provides a set of coefficients which will vary from texture to texture, and is based on linearly predicting the intensity value of a pixel by a weighted sum of surrounding pixels. These weights are the linear prediction coefficients, are assumed to be constant over a given texture, and can be computed by structuring an over-constrained set of linear equations where the coefficients are the unknowns, and using any of the CCD implementable techniques suggested in this report for solving this kind of problem. Once the weights for a particular type of texture are found, then the linear prediction can be applied to the image array as a CCD implementable convolution. The squared error between the predicted value and actual value can then be thresholded to determine whether or not a particular pixel belongs to the texture on which the coefficients were trained. Thus the segmentation is complete. Results of this approach to image segmentation are given in [23]. A filtered version of the image may provide a better texture with which to work, but this is dependent on any assumptions made a priori about the target.

A major assumption made by this algorithm is that some kind of rough segmentation is required to identify the pixels to be used in training the linear predictor coefficients. If the target is expected to be in the center of the image (as during tracking), then the texture filter can be trained there or along the edges.

5.2.6.3 Gestalt Segmentation

In this approach the segmentation method is based on the Gestalt law of common fate, which implies that if several image regions appear to move together, they are treated as a single object. The algorithms used in this technique may be the same as those used for gradient, moment, coordinate, or transform algorithms discussed in earlier sections. Here these algorithms are applied to small nonoverlapping regions within the input image and the movement parameters of each region are computed. Those regions whose parameters are close in some vector norm sense are grouped either to the target or background, thus performing segmentation.

This technique makes the same assumptions as the tracking algorithm being used. The primary difference is that the regions are smaller and fewer points are available for computing the tracking parameters within each region. Also this type of segmentation is rougher, since it assigns regions of pixels to target or background as opposed to individual pixels.

5.2.6.4 Principal Axis Parameter Estimation

Or a binary image is produced from the appropriate segmentation algorithm, an estimate of target position, orientation, and size is needed. The principal axis method first estimates the centroid of the target image by summing the coordinate values of points belonging to the target. The average x and y coordinate that results is used as the position of the target. Next a line which contains that point is obtained by minimizing the sum of the square of the perpendicular distances from all target points to that line with respect to the slope of the line. The angle formed between the line (principal axis) and a reference line yields the angle of orientation. The size estimate is then made by computing the number of pixels classified as belonging to the target. Note that the above calculations can be done with weighted sums of coordinate values, and thus can be implemented with CCDs.

5.2.6.5 Projection Parameter Estimation

A faster algorithm may be provided by this approach. This method first projects the binary image onto the x and y axes. That is, the number of pixels belonging to the target along each row and along each column is computed and stored. As in the principal axis approach the total number of target classified pixels is used as the size estimate. Now however, the position is determined by computing the one-dimensional centroids of the two orthogonal projections. The one-dimensional centroid can be computed by a summation of coordinate values weighted by the number of pixels from the target assigned to that coordinate. The angle of orientation can be computed by performing this one-dimensional centroid calculation on the four sections of the projections separated at the centroids computed earlier. The angle of orientation is thus given by

$$\Theta = \tan^{-1}[(Y^T - Y^B)/(X^T - X^B)] \qquad (5.2.6.1)$$

where Y^T, Y^B, X^T, and X^B are the centroids for the top and bottom y projection and the top and bottom x projection respectively. Note that the computations made by this algorithm can be performed mostly by CCDs.

5.2.6.6 Assumptions

There are several assumptions made by segmentation algorithms. One important assumption is that the entire target is in the field of view of the input image array. This is necessary so that the differentiation between target and background can be used for segmentation and position estimation. Another important assumption is that there is a difference between the target and background, and that the difference is dependent on the application and therefore must be known a priori. This is so the hardware can be structured to segment based on only one type of difference, whether that be intensity differences, texture differences, or motion differences. Although the parameter estimation algorithms are relatively insensitive to a small number of misclassifications, the algorithms will not work well with only a rough segmentation performed.

5.3 Implementation

As a demonstration of the practicality of this algorithm search, an example system is developed in this section. This example is not a proposal for hardware design, nor does it necessarily represent the optimum approach, but it does serve to illustrate the CCD structure of a viable alternative to the proposed system. The design presented in this section is based on the moment tracking algorithm of section 5.2.2 and the Kalman parameter identification algorithm of section 5.2.4. It is assumed that there is a single target centered in the field of view (FOV) occupying a significant area (greater than 1% of FOV). The problem of identifying and locking the target within the field of view is not considered in this design. The overall system configuration is shown in Figure 5-1. The functions of the imager, preprocessor, moment estimator, parameter estimator, and imager controller are discussed individually in the follow sections. In addition, functional diagrams of the moment and parameter estimators are developed. The timing and control functions are discussed within each of the other functional block descriptions.

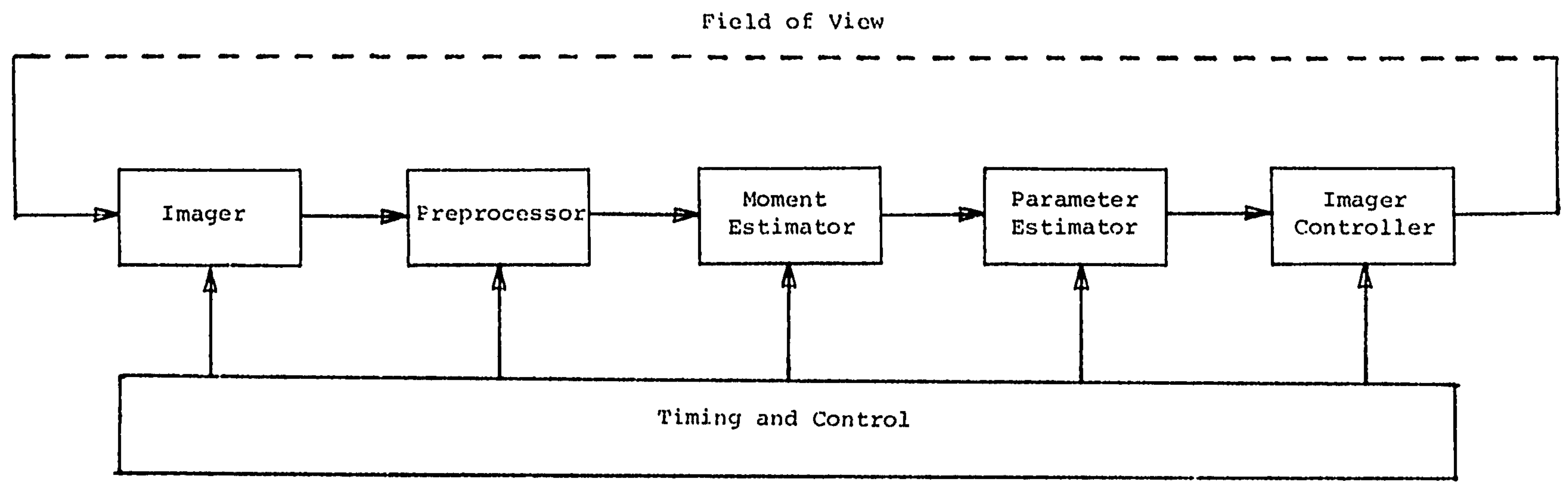


Figure 5.1

Example System Configuration

5.3.1 Imager

The imager is a CCD image array of 10C by 100 pixels. It is highly sensitive to the infrared spectrum, since it is assumed that all targets of interest will appear warm against a cold background. The exposure (integration) time is variable and controlled by the timing and control unit. The amount of exposure is determined by the light intensity of the field of view, so that the contrast between the target and background is sharp enough for accurate identification of target points by their intensity values. A frame rate of 10 frames per second allows a maximum exposure time of .01 seconds and a processing time of .09 seconds before the next frame is exposed. After exposure, the discrete analog data is transferred from the CCD image array one pixel at a time at a 1 MHz rate. A gated 10 KHz clock is used to clock the data up one row with the top row being lost and the bottom row given appropriate values in preparation for the next exposure. The top row is clocked to the right with a 1 MHz clock with a readout on the upper right corner pixel. Thus the data is clocked out with the appropriate signals from the timing and control box in the order shown in Figure 5-2. Note that if the top N rows are not needed, then they may be clocked out at a rapid rate, and readout may start on the N + 1 row.

5.3.2 Preprocessor

The primary function of the preprocessor section is to prepare the data for the moment estimator. This may include low pass filtering to eliminate high frequency noise or weighted correction of nonlinearitics in the imager. In this design, it is used to normalize the data, so that the target contrasts sharply with the background and there are sufficient intensity variations within the target to provide good moment estimates. Histogram equalization is one means of performing this normalization, but the associated hardware

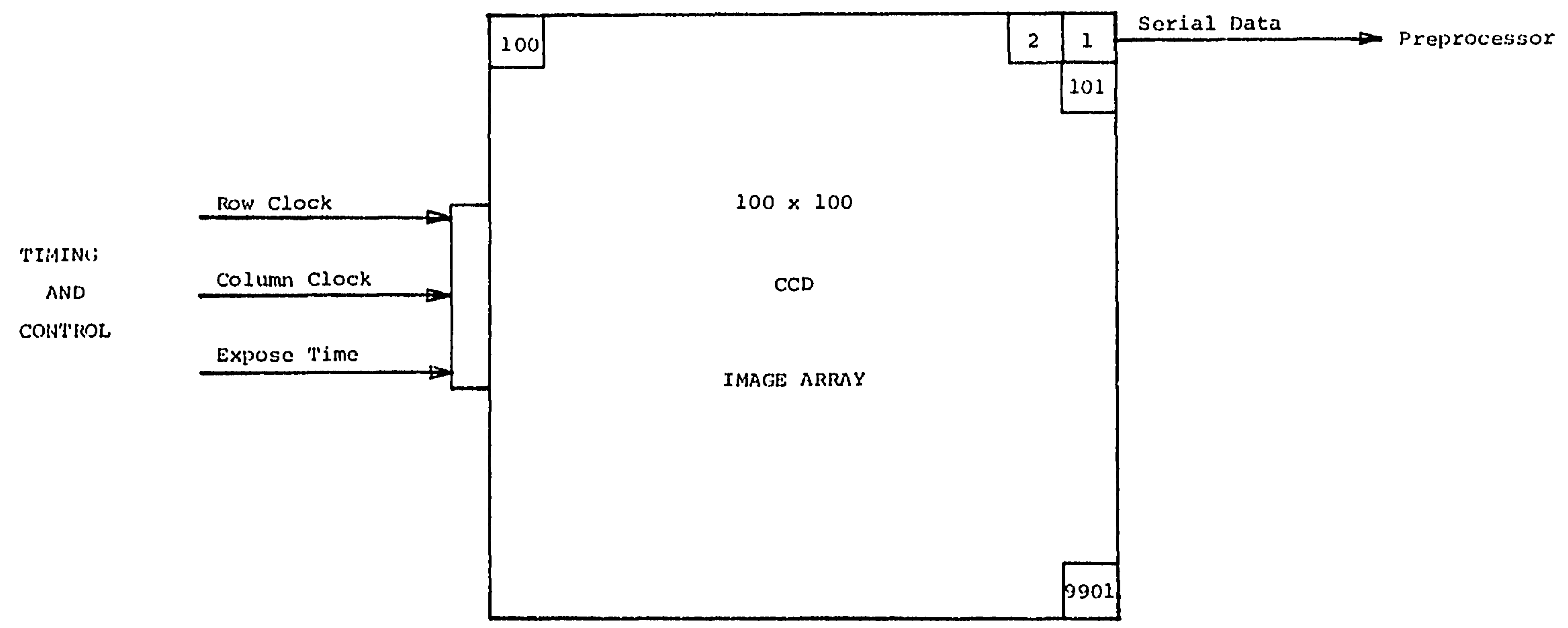


Figure 5.2

Imager With Data Readout Sequence

is too complex. A simpler but effective method is to subtract out the mean of the data at each point, then divide the resulting data by its variance. This will give a normalized data set with zero mean and unit variance.

Another function of this preprocessor is to reduce the bulk of the data. Since the target is assumed to be roughly in the center of the frame, only the center 32 by 32 pixels are kept for processing. Since the timing and control unit knows when each pixel is clocked out of the image array, it can generate the appropriate signals for clocking the center area into a 1024 stage CCD shift register. A diagram of the preprocessor with the data reduction and normalization functions is shown in Figure 5-3.

5.3.3 Moment Estimator

The moment estimator receives the data from the preprocessor and stores it in a 100 stage CCD array, which is tapped in such a way that 4 by 4 square regions are available for moment estimation. These sixteen taps are then multiplied by their digital coordinates and summed to provide the five moment estimates needed for the constrained Affine parameter estimation. Let Figure 5-4 establish a coordinate system. Using the expansion given by (5.2.2.2) and the approximation given by (5.2.2.3) and (5.2.2.4), and constraining the Affine parameters such that $a_{11} = a_{22} = a_1$ and $-a_{12} = a_{21} = a_2$, the basic equation of (5.2.2.1) becomes

$$w(k,t+T) = w(k,t) = a_1x_1(k,t) + a_2x_2(k,t) + b_1x_3(k,t) + b_2x_4(k,t) \tag{5.3.3a}$$

where

$$w(k,t) = \sum_{i=0}^{3} \sum_{j=0}^{3} f(x+i,\ y+j,\ t) \tag{5.3.3b}$$

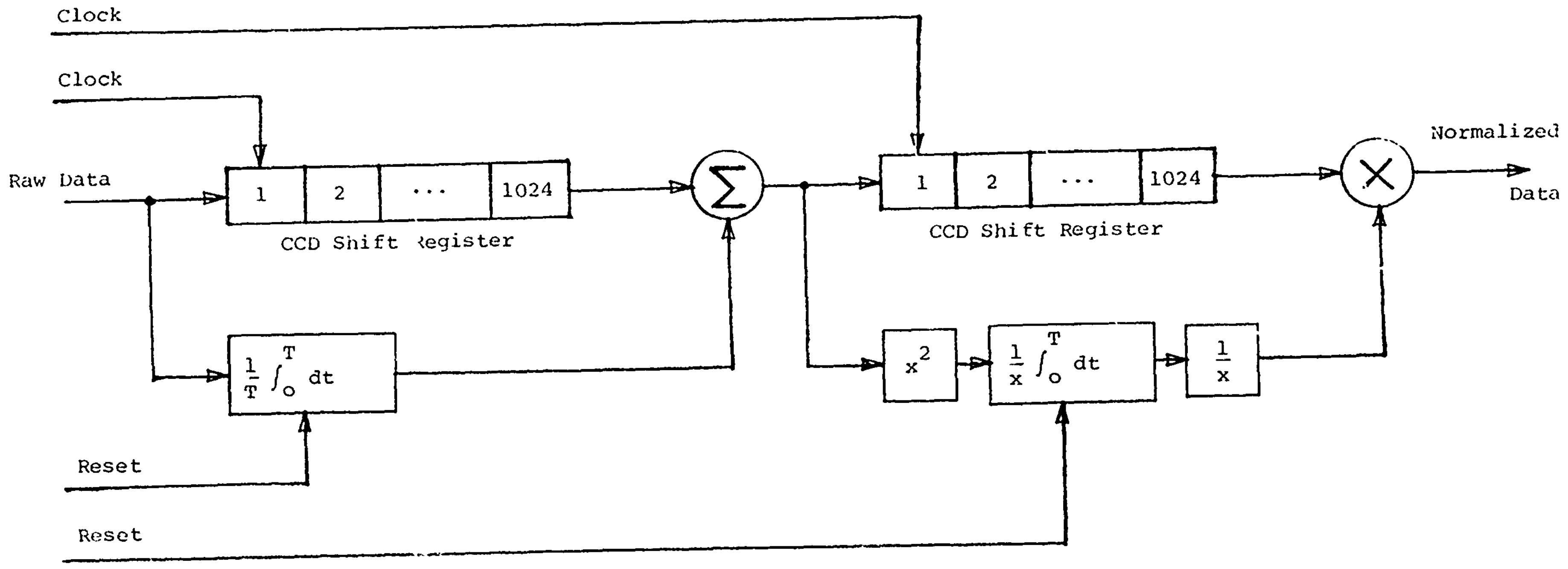


Figure 5.3

Preprocessor with normalization and storage

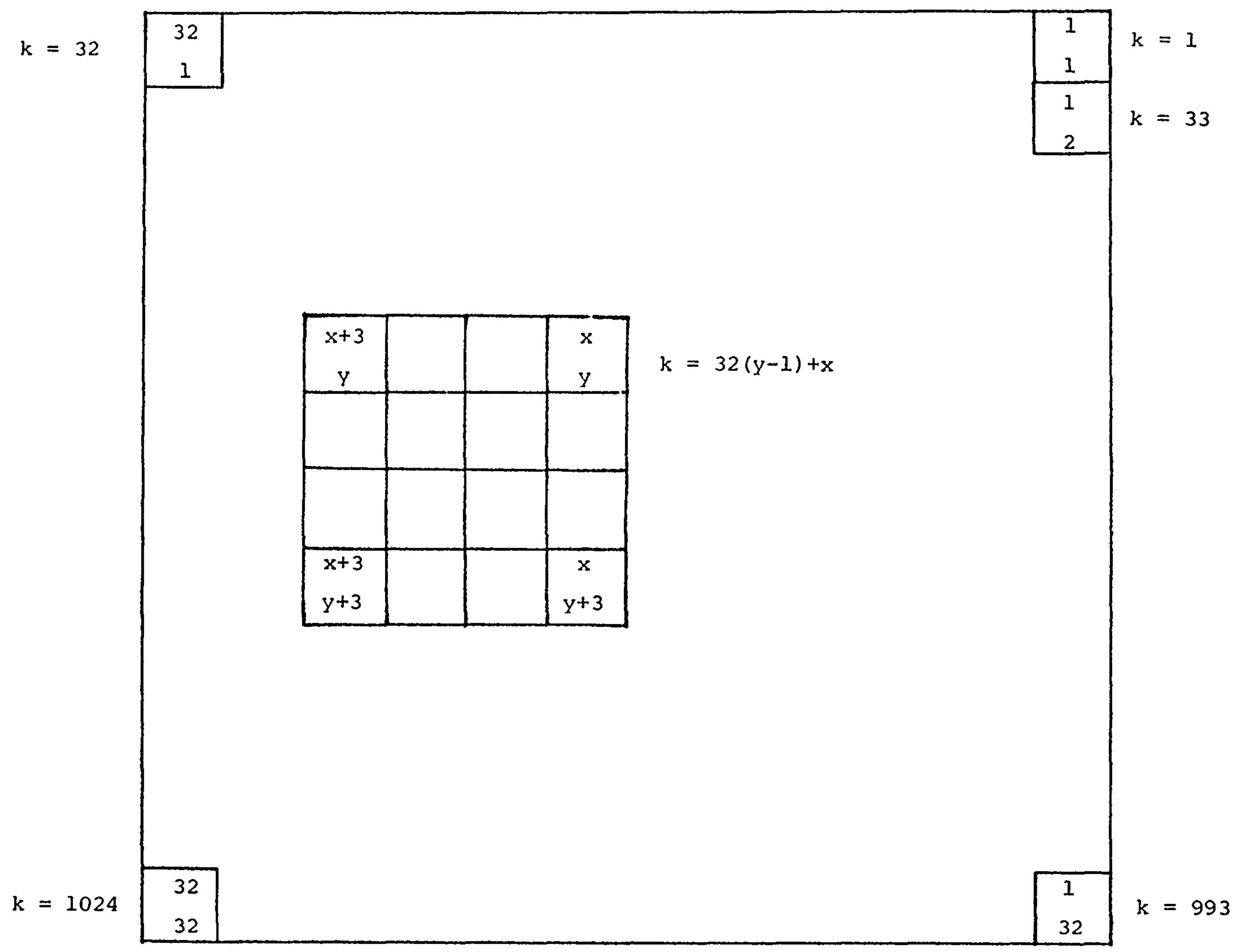


Figure 5-4

Relationship between coordinates and iteration index, k, of a 32 by 32 subimage

$$x_1(k,t) = \sum_{i=0}^{3} [(y+3)f(x+i,\ y+3,\ t) - (y)f(x+i,\ y,\ t)]$$
$$+ \sum_{j=0}^{3} [(x+3)f(x+3,\ y+j,\ t) - (x)f(x,\ y+j,\ t)]$$
$$-2 \sum_{i=0}^{3} \sum_{j=0}^{3} f(x+i,\ y+j,\ t) \qquad (5.3.3c)$$

$$x_2(k,t) = \sum_{i=0}^{3} (x+i)[f(x+i,\ y+3,\ t) - f(x+i,\ y,\ t)]$$
$$- \sum_{j=0}^{3} (y+j)[f(x+3,\ y+j,\ t) - f(x,\ y+j,\ t)] \qquad (5.3.3d)$$

$$x_3(k,t) = \sum_{j=0}^{3} [f(x+3,\ y+j,\ t) - f(x,\ y+j,\ t)] \qquad (5.3.3e)$$

and

$$x_4(k,t) = \sum_{i=0}^{3} [f(x+i,\ y+3,\ t) - f(x+i,\ y,\ t)] \qquad (5.3.3f)$$

Note that these sums of products are CCD implementable. The coordinates are digital values supplied by the timing and control unit, thus every multiplication is analog by digital with analog output and every summation is analog. The diagram of the hardware needed for this moment estimator is shown in Figure 5-5. Figures 5-6 and 5-7 show further details of the multiplication and summation sections.

5.3.4 Parameter Estimator

The parameter estimator implements the Kalman estimator as given in (5.2.4.5) and is formulated for this problem as:

$$A(k+1) = A(k) + V_A(k)X(k)[Z(k) - A^T(k)X(k)]/\rho(k) \qquad (5.3.4a)$$

$$V_A(k+1) = V_A(k) + V_u - V_A(k)X(k)X^T(k)\ V_A(k)/\rho(k) \qquad (5.3.4b)$$

where

$$\rho(k) = V_V^2 + X^T(k)V_A(k)X(k) \qquad (5.3.4c)$$

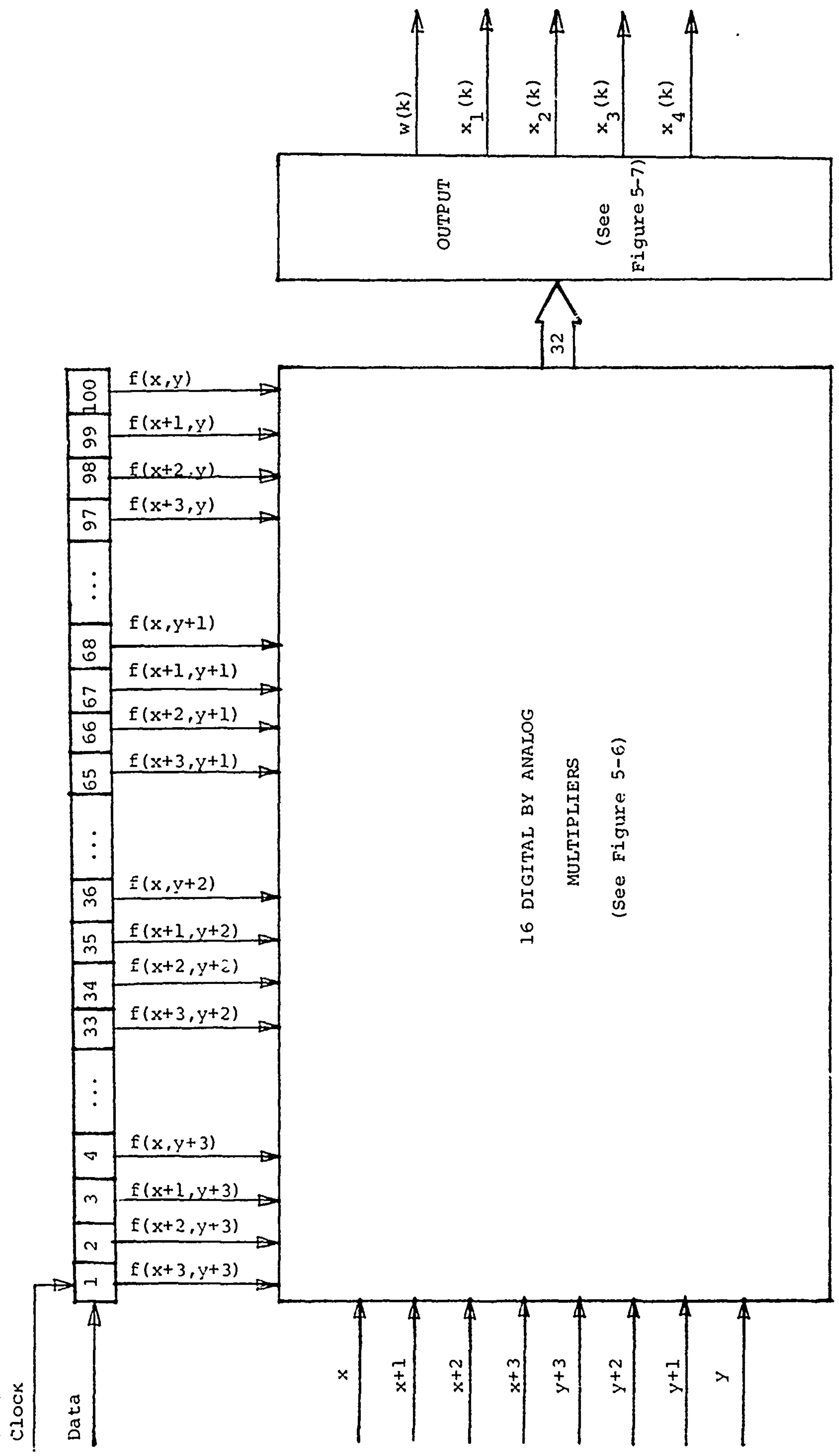


Figure 5.5
Moment Estimator

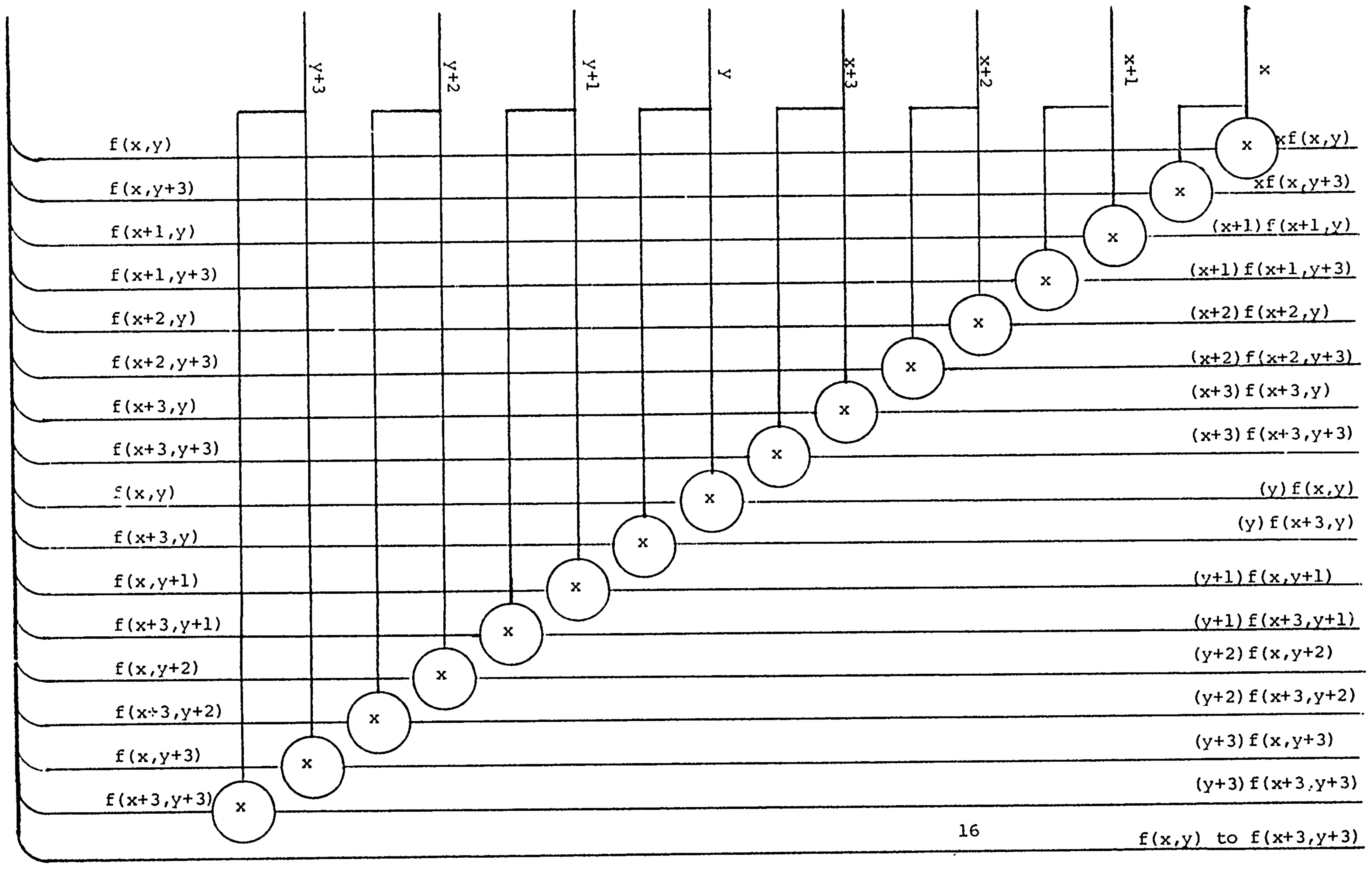


Figure 5.6

Digital by analog multipliers for moment estimator

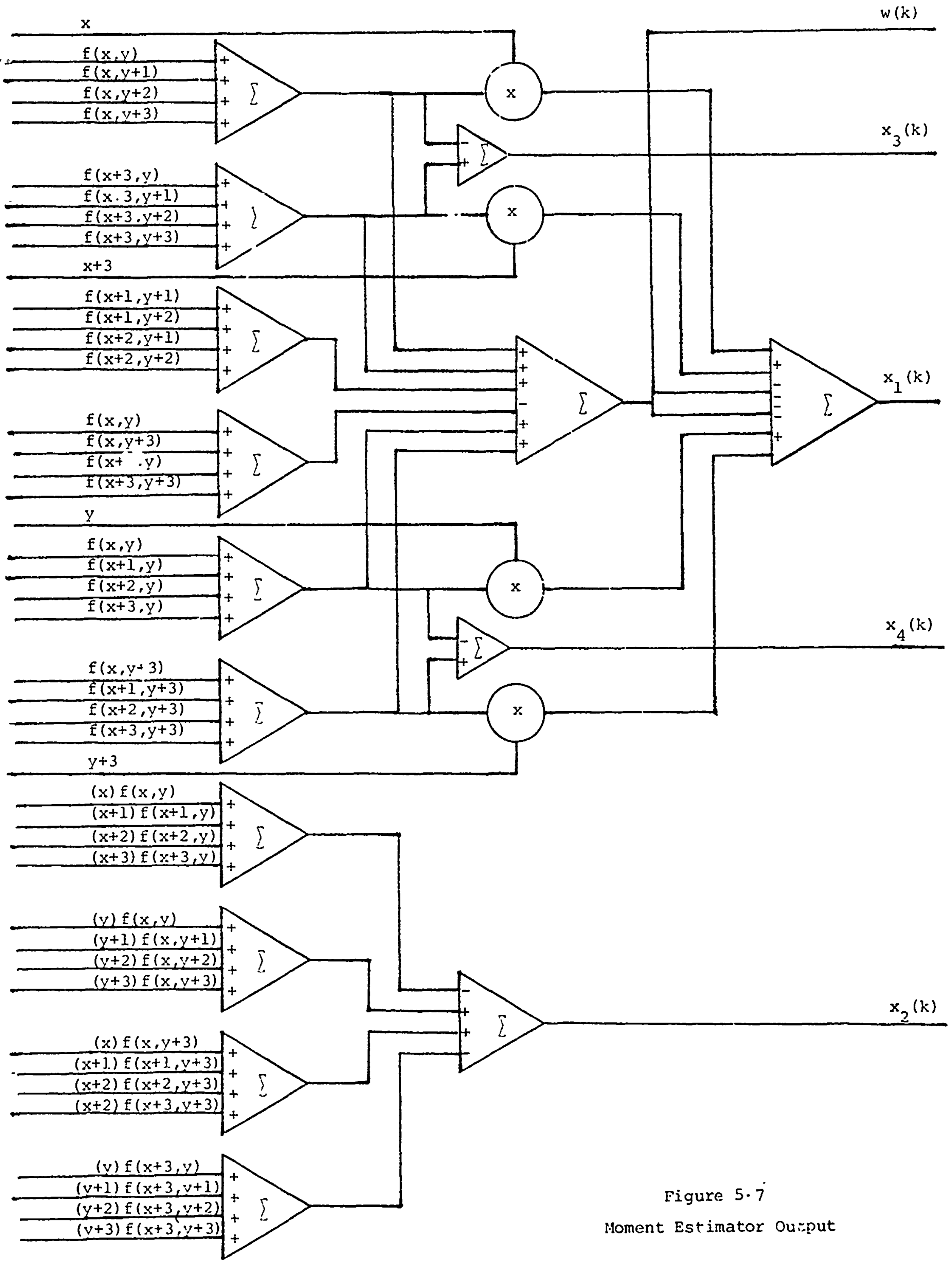


Figure 5·7

Moment Estimator Output

$$A(k) = [a_1(k,t) \quad a_2(k,t) \quad b_1(k,t) \quad b_2(k,t)]^T \tag{5.3.4d}$$

$$x(k) = [x_1(k,t) x_2(k,t) \quad x_3(k,t) \quad x_4(k,t)]^T \tag{5.3.4e}$$

and

$$Z(k) = W(k,t) - W(k,t-T) \tag{5.3.4f}$$

Note that A(0), $V_A(0)$, V_V and V_U must be initialized to some value before processing.

The complexity of this algorithm requires high speed processing. Therefore, special purpose digital hardware is used to implement this function. Due to the high speed requirements, as much of the processing as possible is performed in parallel. A diagram of the hardware implementation of this algorithm is shown in Figure 5-8.

5.3.5 Imager Controller

The imager controller consists of that hardware which controls the field of view for the image array. In this application, it is assumed that the image array is located in a small enclosure which can pan left and right or tilt up and down. Also a lens system allows zoom and focus control. The imager controller receives the parameter estimates from the parameter estimator, refines these estimates using the estimates from the previous frames, then generates the appropriate control signals to center the target within the field of view. The hardware involved in this implementation is beyond the scope of this investigation, and thus will not be presented in this section.

5.4 Summary

Several algorithms for performing image tracking have been presented in this section. A CCD based implementation with analog and digital support has been suggested for each algorithm, and thus each one appears to be feasible

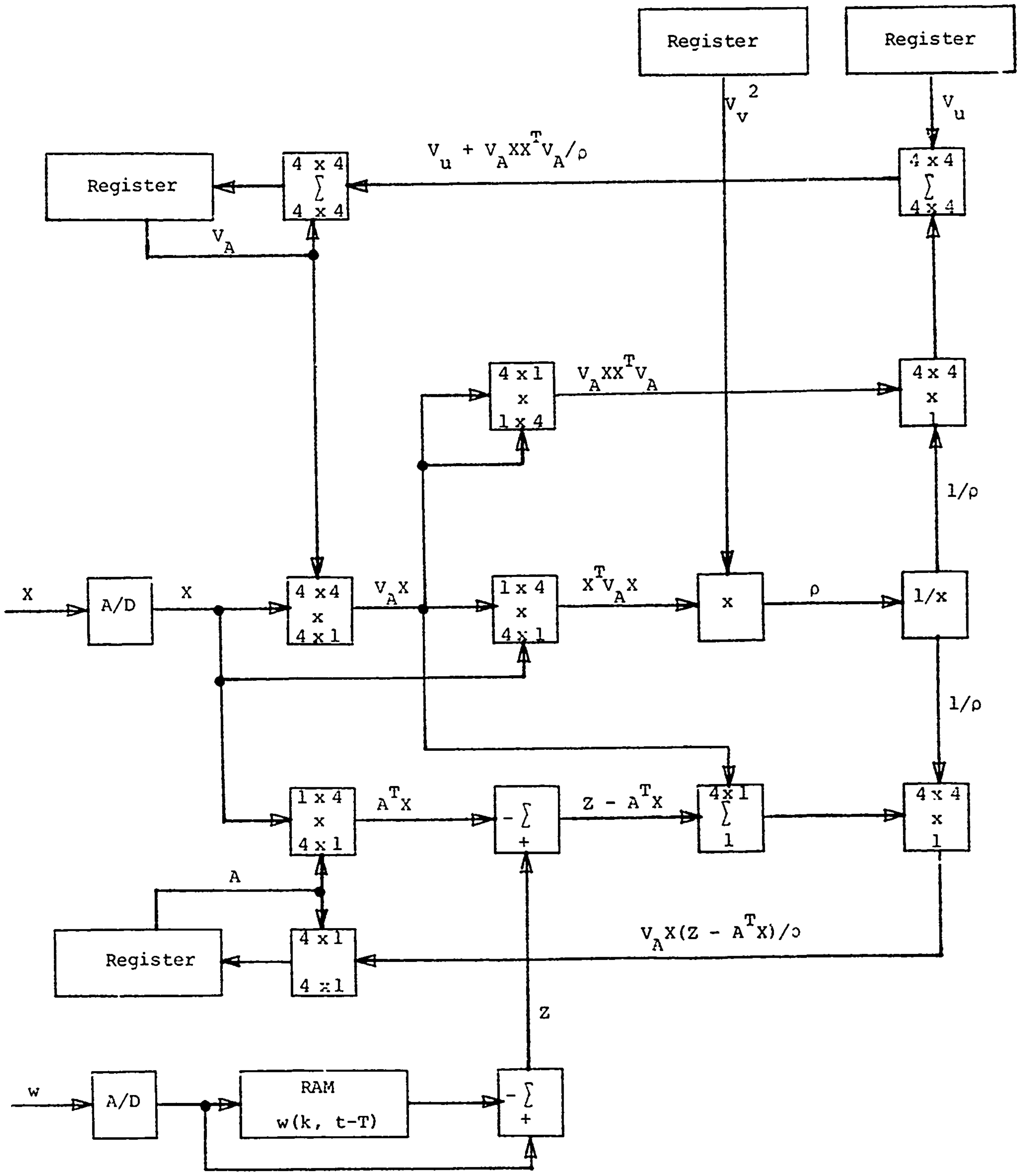


Figure 5-8

Digital Kalman parameter estimator

for use either as a substitute for the TSVIP algorithm or as a support algorithm for it. Further studies will be required to make this determination.

There are distinct advantages and disadvantages among the algorithms. The segmentation algorithms provide better lock capabilities than the gradient, moment, or coordinate based algorithms, since they provide absolute tracking measurements referenced to a fixed coordinate system as opposed to relative tracking measurement referenced to the previous frame. The transform based algorithms require more computations than the other algorithms. The sequential solution offered by the Kalman estimator or the Widrow-Hoff estimator has a more efficient hardware structure than a pseudo-inverse implementation, but a slow rate of convergence could easily offset this advantage. The segmentation and transform algorithms can tolerate a slower sampling rate even for fast targets, while the coordinate algorithms can tolerate a lower spatial sampling rate. All the algorithms can model rotation, dilation, and translation, but the segmentation algorithms are not affected by any movements. They are affected however by changes in texture or intensity. The gradient algorithms are very noise sensitive.

Thus there are many advantages and disadvantages that can now be observed among the possible algorithms. Table 5-1 roughly summarizes these, but the final decision must be based on simulation studies and hardware proposals. A program to simulate a moving target has been developed. This will provide a common data base to test the algorithms. The algorithms need to be developed as computer programs, and performance indices must be created to measure their performance with the common data base. A supplementary report on this task giving a summary of the performance data will be provided later, or the information will be available from a journal publication.

	GRADIENT	MOMENT	COORDINATE	TRANSFORMATION	SEGMENTATION
Computational Simplicity	4	4	2	2	3
CCD Implementability	5	5	4	3	5
Noise Immunity	1	3	4	3	4
Segmentation Immunity	4	4	1	4	2
Tracking Error Immunity	2	2	2	4	5
Spatial Sampling Immunity	2	3	4	3	5
Time Sampling Immunity	2	2	2	4	5

Legend:
1 = Poor
2 = Moderately Poor
3 = Fair
4 = Moderately Good
5 = Good

Table 5-1

Algorithm Comparison Chart

CHAPTER VI

RECOMMENDED FUTURE RESEARCH

Tracking and guidance using computer vision has much to offer in both military and civilian applications for a broad spectrum of activities. Systems that can look over the horizon and recognize specific patterns and then provide homing signals have many generic problems that are identical to those of systems which pick cabbages from a moving vehicle or perform tasks on the factory floor, so military technology will benefit from advanced automation and other computer vision research in progress both here and abroad. However, some research dedicated to tracking and guidance is required to be certain that problems specific to this area are solved in a timely manner.

Our results on CCD architectures for signal processing are encouraging. But, the practical and conceptual problems can be solved only through continued research. This technology provides one of the best possibilities for rapidly processing the very large quantities of data needed to realize high level, real time computer vision. The problems of size and reliability are of the utmost importance if systems are to be installed on small carriers and, here again, CCDs offer a possible solution. Separate research on CCD basic building blocks for signal processing is recommended if a unified research program is not continued.

The realization of practical computer vision tracking with a high degree of confidence is expected to require a hierarchy of algorithms working together to accommodate the wide variety of environmental conditions that can be encountered. The algorithms will include multiple solutions for measuring motion in three dimensions, segmenting, edging, recognition and capability of accommodating multiple targets; and all of this in a noisy environment which partly, or occasionally completely, obscures the target. General algorithm work and testing will undoubtedly be a long term area of research, certainly in the next five to ten year time frame.

It is important that experimental work accompany the theoretical work. A computer vision tracking and guidance laboratory should be established to test and refine algorithms and to help delineate the problems that can be discovered only through hardware experimentation. The laboratory needs working systems and target simulation capability. We have reached the first performance level with our experimental system, but the components were originally built or acquired for manufacturing automation. Equipment designed for this specific problem is needed, including a dedicated digital computer. The establishment of such a laboratory is recommended because of the fundamental importance of small computer vision based tracking and guidance systems.

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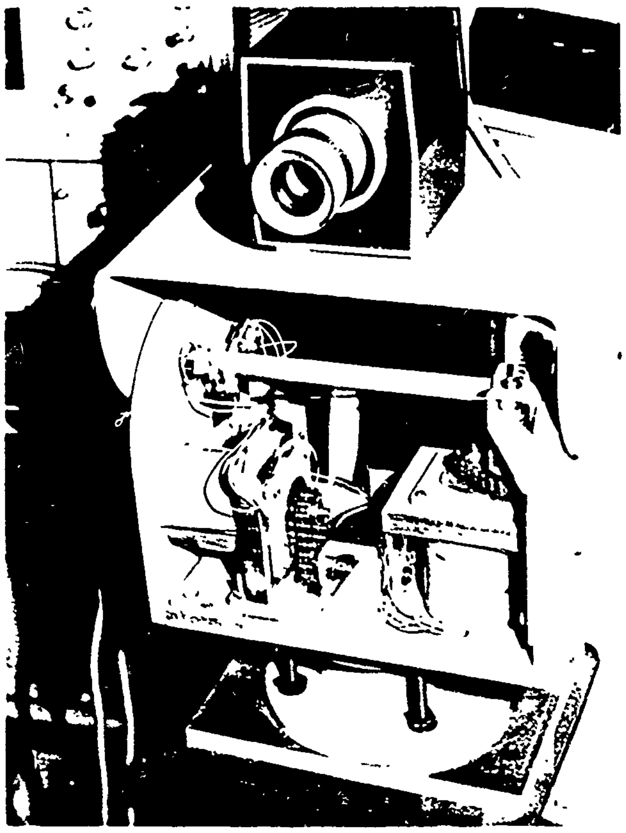
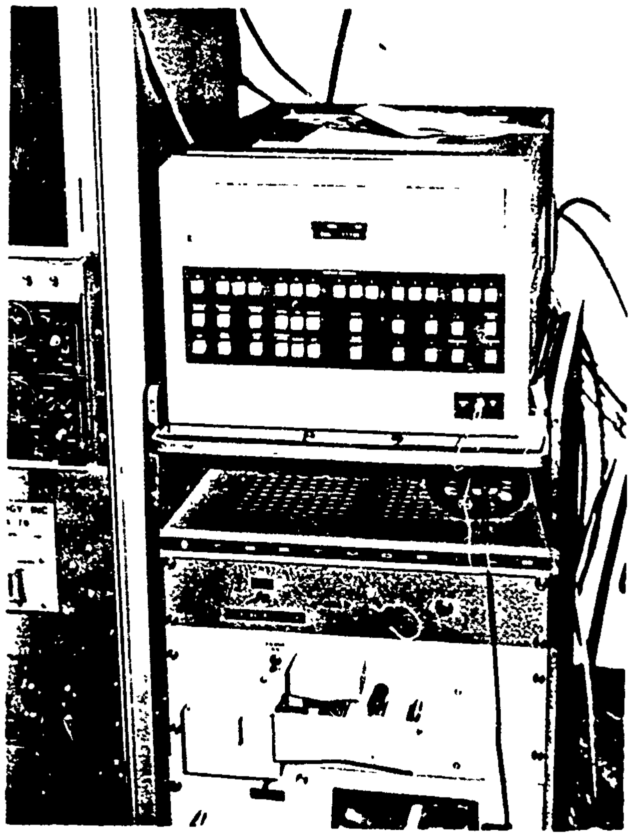
Appendix 2.1: Pin Connections for Video Interface Cable

TO EXTERNAL DEVICE		
SIGNAL	PIN	DEVICE END CONTINENTAL CONNECTOR PIN
BIT 0	A	A
BIT 1	B	E
BIT 2	C	K
BIT 3	D	P
BIT 4	E	U
BIT 5	F	Y
BIT 6	H	c
BIT 7	J	h
BIT 8	K	n
BIT 9	L	t
BIT 10	M	x
Bit 11	N	BB
BIT 12	P	FF
BIT 13	R	C
BIT 14	S	H
BIT 15	T	M
DEVICE COMMAND	22,Z	k,r
GROUND	BB	DD

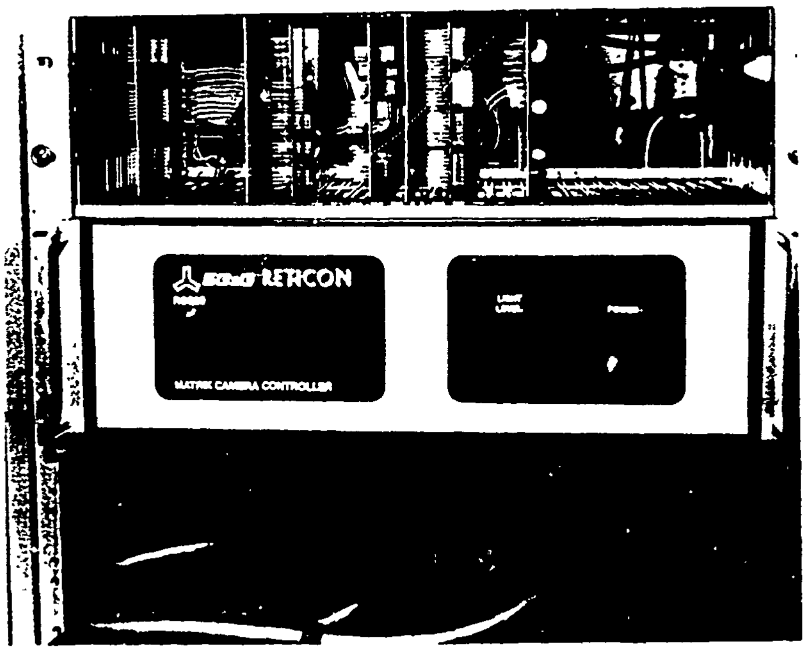
Appendix 2.2: Photographs of Tracking System



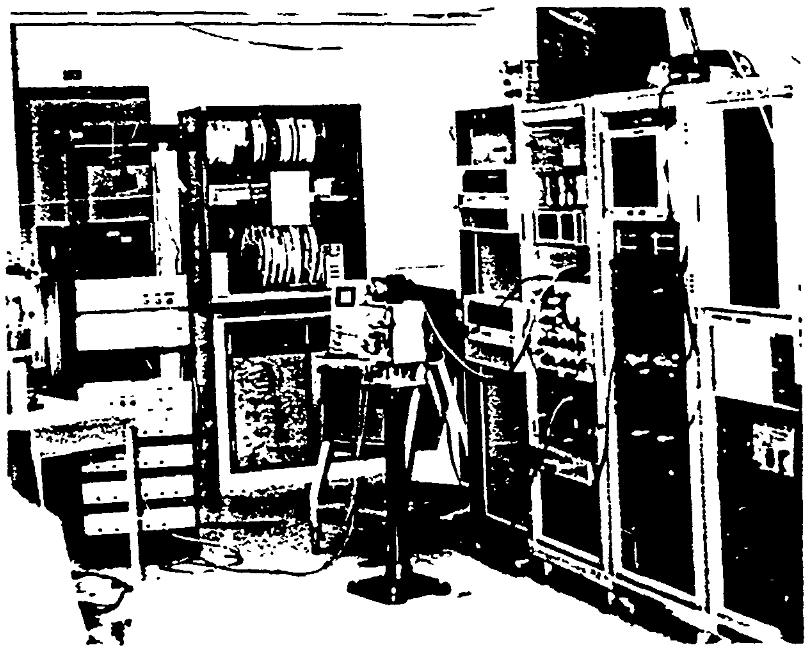
Photograph of camera and pan tilt mount.



Photograph of HP2100 minicomputer.



Photograph of camera controller



Overall view of tracking system

```
      PAGE 0001            FTN4 COMPILER: HP24177  (SEPT. 1974)

          FTN4,L
      C
      C
          PROGRAM CONT
      C
      C
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CC                                                                       CC
      CC                                                                       CC
      CC  THE PURPOSE OF THIS ROUTINE IS TO PROVIDE THE OVERALL CONTROL        CC
      CC  FOR THE TRACKING SYSTEM.                                             CC
      CC                                                                       CC
      CC  SOURCE FILE:           CONTS                                         CC
      CC  OBJECT FILE:           CONTR                                         CC
      CC                                                                       CC
      CC  THIS PROGRAM CALLS THE FOLLOWING ROUTINES:                           CC
      CC      INIT               INITIALIZE CONTROL VARIABLES                  CC
      CC      UTIL               READ IN DATA ARRAY AND COMPUTE PC, G,         CC
      CC                         & MEAN                                        CC
      CC      TRACK              COMPUTE ESTIMATES FOR AFFINE PARAMETERS       CC
      CC      DRIVE              MODIFY CAMERA POSITION                        CC
      CC      MOTOR              DRIVER FOR PAN TILT MOUNT                     CC
      CC                                                                       CC
      CC  POS1 & POS2            CURRENT CAMERA POSITION                       CC
      CC  DUMP                   4 X 1 ARRAY OF DATA DUMP PARAMETERS           CC
      CC  IMOVE                  CONTROL OPTION                                CC
      CC  MEAN1 & MEAN2          MEANS OF SCENE 1 AND 2                        CC
      CC  ITEST                  INPUT TEST VARIABLE                           CC
      CC  G & PC                 ARRAYS OF WEIGHTED AND UNWEIGHTED             CC
      CC                         SPATIAL DERRIVATIVES                          CC
      CC  D1 & D2                TARGET VECTORS OF SCENES 1 & 2                CC
      CC  A                      4 X 1 ARRAY OF AFFINE ESTIMATES               CC
      CC  JSTEP                  MAXIMUM CAMERA DISPLACEMENT FROM ORIGIN       CC
      CC  JAVG                   NUMBER OF AVERAGES PER COMPUTED ESTIMATE      CC
      CC  JDIS, JHOR, & JVER     DIRECTION OF DISPLACEMENT                     CC
      CC  SCALE                  NOISE ADJUSTMENT FACTOR                       CC
      CC  PIC                    IMAGE DATA ARRAY                              CC
      CC                                                                       CC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      C
      C
          INTEGER ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
          INTEGER JPOS1,JPOS2,IODEV,IDISP,IVIEW,IDOPT,IMOVE,PMAG,I0,J0
          INTEGER ISTEP1,ISTEP2,IDIR,POS1,POS2,IPOS,JPOS,I,J,PIC(100,100)
          INTEGER DUMP(4),JDIS,JAVG,JSTEP,JVER,JHOR
          REAL A(4,1),G(20,2),PC(20,2),MEAN1,MEAN2,SCALE,PT(2,20)
          COMMON ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
          COMMON JPOS1,JPOS2,IODEV,IDISP,IVIEW,IDOPT,IMOVE,PMAG,I0,J0
          COMMON ISTEP1,ISTEP2,IDIR,POS1,POS2
      C
      C
      C   INITIALIZE CONSTANTS
          CALL INIT
      C

      PAGE 0002 CONT       FTN4 COMPILER: HP24177  (SEPT. 1974)

      C   CURRENT CAMERA POSITION IS ASSUMED TO BE ORIGIN
```

140

```
C
C     STORE ARRAY DUMP PARAMETERS
      DUMP(1)=IPOS1
      DUMP(2)=IPOS2
      DUMP(3)=JPOS1
      DUMP(4)=JPOS2
C
C     HUMAN TARGET CONTROL
      IF (IMOVE.NE.0) GO TO 400
      CALL UTIL(1,PIC,DUMP,D1,D2,MEAN1,G,PC)
      WRITE (1,100)
  100 FORMAT ("ENTER 0 FOR SIMULATED AND 1 FOR REAL TARGET MOTION")
      READ (1,*) ITEST
  200 IF (ITEST.EQ.0) CALL PERT(PIC,IMAX,JMAX)
      IF (ITEST.EQ.1) CALL DRIVE
      CALL UTIL(2,PIC,DUMP,D1,D2,MEAN2,G,PC)
      SCALE=MEAN1/MEAN2
      CALL TRACK(K,PC,G,SCALE,D1,D2,A)
      WRITE (1,300) POS1,POS2,A(3,1),A(4,1)
  300 FORMAT (4F4.2)
      GO TO 200
C
C     AUTOMATIC TARGET CONTROL
  400 IF (IMOVE.NE.1) GO TO 1200
      WRITE (1,500)
  500 FORMAT("ENTER DISPLACEMENT AND NUMBER OF AVERAGES")
      READ (1,*) JSTEP,JAVG
      WRITE (1,600)
  600 FORMAT ("ENTER 0 FOR HORIZONTAL OR 1 FOR VERTICAL DISPLACEMENT")
      READ (1,*) JDIS
      JVER=1
      JHOR=0
      IF (JDIS.NE.1) GO TO 700
      JVER=0
      JHOR=1
  700 DO 1000 J=1,JAVG
      CALL UTIL(1,PIC,DUMP,D1,D2,MEAN1,G,PC)
      DO 900 JJ=1,JSTEP
      CALL MOTOR(12,JVER*ISTEP1,JHOR*ISTEP2,3,3)
      CALL UTIL(2,PIC,DUMP,D1,D2,MEAN2,G,PC)
      SCALE=MEAN1/MEAN2
      CALL TRACK(K,PC,G,SCALE,D1,D2,A)
      WRITE (1,800) JJ,J,A(3,1),A(4,1),POS1,POS2
  800 FORMAT (2I6,2F4.2,2I6)
      PT(1,JJ)=(A(3,1)+(J-1)*PT(1,JJ))/J
      PT(2,JJ)=(A(4,1)+(J-1)*PT(2,JJ))/J
  900 CONTINUE
      CALL MOTOR(12,JVER*JSTEP*ISTEP1,JHOR*JSTEP*ISTEP2,0,3)
      POS1=0
      POS2=0
 1000 CONTINUE
      WRITE (IODEV,1100) ((PT(I,J),I=1,2),J=1,JSTEP)
 1100 FORMAT (2F4.2)

        PAGE 0003  CONT    FTN4 COMPILER: HP24177  (SEPT. 1974)

      STOP
C
C     CLOSED LOOP OPERATION
 1200 CALL UTIL(1,PIC,DUMP,D1,D2,MEAN1,G,PC)
 1300 CALL UTIL(2,PIC,DUMP,D1,D2,MEAN2,G,PC)
      SCALE=MEAN1/MEAN2
      CALL TRACK(K,PC,G,SCALE,D1,D2,A)
      CALL PAINT(A(3,1),A(4,1))
```

```
0122   1400 FORMAT (2I6)
0123        GO TO 1300
0124   C
0125   C
0126        END

**  NO ERRORS**    PROGRAM = 10913      COMMON = 00024

          PAGE  0004  CONT    FTN4 COMPILER: HP24177  (SEPT. 1974)

0127        END$
```

```
      FTN4,L
C
C
      SUBROUTINE INIT
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                    CC
CC                                                                    CC
CC    THE PURPOSE OF THIS ROUTINE IS TO LOAD CONTROL CONSTANTS FOR    CC
CC    THE INTERACTIVE TRACKING SOFTWARE PACKAGE. IF ANY NON-NUMERIC   CC
CC    VALUE IS ENTERED FOR THE VARIOUS READ STATEMENTS THEN THE       CC
CC    PROGRAM WILL DEFAULT TO THE GIVEN VALUES.                       CC
CC                                                                    CC
CC    SOURCE FILE:              INITS                                 CC
CC    OBJECT FILE:              INITR                                 CC
CC    CALLED BY:                MAIN                                  CC
CC                                                                    CC
CC    ISTART                    STARTING ADDRESS FOR CAMERA WINDOW    CC
CC                              IN X DIMENSION                        CC
CC    JSTART                    STARTING ADDRESS FOR CAMERA WINDOW    CC
CC                              IN Y DIMENSION                        CC
CC    ISTOP                     STOPPING ADDRESS FOR CAMERA WINDOW    CC
CC                              IN X DIMENSION                        CC
CC    JSTOP                     STOPPING ADDRESS FOR CAMERA WINDOW    CC
CC                              IN Y DIMENSION                        CC
CC    IDISP                     SCENE DISPLAY OPTION                  CC
CC                              IDISP=2   DUMP DATA ARRAY             CC
CC                              IDISP=1   DISPLAY EACH SCENE          CC
CC                              IDISP=0   NO OUPUT                    CC
CC    MMAG                      MAGNIFICATION FACTOR FOR DISPLAYED SCENE CC
CC    IO                        X ADDRESS ON TEKTRONIX DISPLAY        CC
CC    JO                        Y ADDRESS ON TEKTRONIX DISPLAY        CC
CC    IVIEW                     DERRIVATIVE DISPLAY OPTION            CC
CC                              IVIEW=1   DISPLAY DERRIVATIVES        CC
CC                              IVIEW=0   NO OUPUT                    CC
CC    IDOPT                     DERRIVATIVE COMPUTATION OPTION        CC
CC                              IDOPT=1   WITH AVERAGING              CC
CC                              IDOPT=0   NORMAL                      CC
CC    IMOVE                     AUTOMATIC CONTROL OPTION              CC
CC                              IMOVE=2   CLOSED LOOP                 CC
CC                              IMOVE=1   AUTOMATIC TARGET MOVEMENT   CC
CC                              IMOVE=0   HUMAN CONTROL               CC
CC    IMAX                      NUMBER OF SAMPLES IN X DIMENSION      CC
CC    JMAX                      NUMBER OF SAMPLES IN Y DIMENSION      CC
CC    ICOUNT                    TOTAL NUMBER OF SAMPLES               CC
CC                                                                    CC
CC                                                                    CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      INTEGER JPOS1,JPOS2,IODEV,IDISP,IVIEW,IDOPT,IMOVE,MMAG,IO,JO
      INTEGER ISTEP1,ISTEP2,IDIR,POS1,POS2
      COMMON JPOS1,JPOS2,IODEV,IDISP,IVIEW,IOOPT,IMOVE,PMAG,I0,J0
      COMMON ISTEP1,ISTEP2,IDIR,POS1,POS2
C
C
      ISTART=1
      JSTART=1
      ISTOP=99
      JSTOP=99
      IDISP=0
      PMAG=2
      I0=0
      J0=0
      IVIEW=0
      IOOPT=1
      IMOVE=0
      IODEV=1
C
C
      WRITE (1,100)
  100 FORMAT("ENTER D FOR DEFAULT",//)
C
      WRITE (1,200)
  200 FORMAT ("ENTER ISTART,JSTART,ISTOP,JSTOP")
      READ (1,*) ISTART,JSTART,ISTOP,JSTOP
C
      WRITE (1,300)
  300 FORMAT ("ENTER DISPLAY OPTION: 0 NONE: 1 DISPLAY PICTURE: 2 DUMP")
      READ (1,*) IDISP
      IF (IDISP.NE.1) GO TO 400
      IF (IDISP.NE.1) GO TO 500
         WRITE (1,400)
  400    FORMAT ("ENTER MAGNIFICATION AND COORDINATES OF SCENE")
         READ (1,*) PMAG,I0,J0
  500 IF (IDISP.NE.2) GO TO 700
         WRITE (1,600)
         READ (1,*) IPOS1,IPOS2,JPOS1,JPOS2
  600    FORMAT ("ENTER LOCATION OF DATA TO BE VIEWED")
         READ (1,*) IPOS1,IPOS2,JPOS1,JPOS2
C
  700 WRITE (1,800)
  800 FORMAT ("ENTER DERR. DISPLAY OPTION: 0 NO DISPLAY: 1 DISPLAY")
      READ (1,*) IVIEW
C
      WRITE (1,900)
  900 FORMAT ("ENTER DERR. CALC. OPTION: 0 NORMAL: 1 FOR AVERAGING")
      READ (1,*) IOOPT
C
      WRITE (1,1000)
 1000 FORMAT ("CONTROL OPTION: 0 OPERATOR: 1 AUTOMATIC: 2 CLOSED LOOP")
      READ (1,*) IMOVE
C
      WRITE (1,1100)
 1100 FORMAT ("ENTER OUTPUT DEVICE USED FOR ESTIMATES")
      READ (1,*) IODEV
C

PAGE 0003 INIT    FTN4 COMPILER: HP24177 (SEPT. 1974)

      WRITE (1,1200)
 1200 FORMAT ("MINIMUM STEP SIZE MOVEMENT OF CAMERA")
      READ (1,*) ISTEP1,ISTEP2
C
      IMAX=ISTOP-ISTART+1
      JMAX=JSTOP-JSTART+1
      [illegible]
      RETURN
C
C
      END

** NO ERRORS**    PROGRAM = 00465      COMMON = 00024

          PAGE 0004  INIT    FTN4 COMPILER: HP24177 (SEPT. 1974)

      ENDS
      FTN4,L
C
C
      SUBROUTINE UTIL(IFLAG,PIC,DUMP,D1,D2,MEAN,G,PC)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                      CC
CC                                                                      CC
CC    THE PURPOSE OF THIS ROUTINE IS TO PERFORM GENERAL OUTPUT          CC
CC    OPERATIONS IN THE TRACKING SOFTWARE PACKAGE.                      CC
CC                                                                      CC
CC    SOURCE FILE:            UTILS                                     CC
CC    OBJECT FILE:            UTILR                                     CC
CC    CALLED BY:              CONT                                      CC
CC                                                                      CC
CC    THIS PROGRAM CALLS THE FOLLOWING SUBROUTINES:                     CC
CC        CAS                 READ DATA ARRAY FROM CAMERA               CC
CC        SORT                REPACKS THE CAMERA DATA ARRAY             CC
CC        RECT                PERFORMS TARGET / BACKROUND SEPARARTION   CC
CC        ILOAD               STORES INTERIOR TARGET PTS TO CREATE D    CC
CC        DERV                CREATES DERRIVATIVE ARRAYS: PC & G        CC
CC        DISP                OUTPUTS DIGITAL IMAGE ON TEKTRONIX        CC
CC                                                                      CC
CC    IFLAG                   SCENE INDICATOR: 1 INITIAL: 2 SECOND      CC
CC    D1 & D2                 N X 1 ARRAYS CONTAINING TARGET POINTS     CC
CC    IDISP                   OUTPUT CONTROL VARIABLE: 1 DISPLAY IMAGE  CC
CC                            2 DUMP SECTOR OF IMAGE: 3 DISPLAY IMAGE   CC
CC                            WITH TARGET BLANKING                      CC
CC    RMIN & RMAX             RANGE OF VALUES IN DATA ARRAY             CC
CC    PIC                     INTEGER DATA ARRAY                        CC
CC    DUMP                    4 X 1 ARRAY CONTAINING LOCATION OF        CC
CC                            SECTOR TO BE VIEWED                       CC
CC    IPOS1 & IPOS2           TARGET PROJECTION ON X AXIS               CC
CC    JPOS1 & JPOS2           TARGET PROJECTION ON Y AXIS               CC
CC    I & J                   DO LOOP CONTROL VARIABLES                 CC
CC    PC & G                  ARRAYS OF WEIGHTED AND UNWEIGHTED         CC
CC                            SPATIAL DERRIVATIVES                      CC
CC    MEAN                    MEAN INTENSITY OF DATA ARRAY              CC
CC                                                                      CC
CC                                                                      CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      INTEGER JPOS1,JPOS2,ILEV,IDISP,IVIEW,IDOPT,IMOVE,RMAG,IR,JR
      INTEGER ISTEP1,ISTEP2,IDIR,POS1,POS2,IPOS,JPOS,I,J,PIC(100,100)
      INTEGER DUMP(4)
      REAL D1(200),D2(200),G(200,2),PC(200,2),MEAN
      COMMON ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      COMMON JPOS1,JPOS2,ILEV,IDISP,IVIEW,IDOPT,IMOVE,RMAG,IR,JR
      COMMON ISTEP1,ISTEP2,IDIR,POS1,POS2
C
C
```

```
C     READ & REPACK CAMERA ARRAY
```

```
      CALL [illegible]
C
C     SECOND SCENE: STORE TARGET POINTS
      IF (IFLAG.EQ.2) CALL DLOAD(PIC,D2)
C
C     FIRST SCENE: SEGMENT: STORE TARGET POINTS: CALCULATE DERRIVATIVES
      IF (IFLAG.NE.1) GO TO 100
      CALL RECT(PIC)
      CALL DLOAD(PIC,D1)
      CALL DERV(PIC,G,PC,K)
C
C     DUMP SECTOR OF DATA ARRAY
  100 IF (IDISP.NE.2) GO TO 700
          WRITE (1,200)
          WRITE (1,200) IPOS1,IPOS2,JPOS1,JPOS2
  200     FORMAT (4I6)
          DO 600 I=DUMP(1),DUMP(2)
              DO 400 J=DUMP(3),DUMP(4)
                  WRITE (1,300) PIC(I,J)
  300             FORMAT (10I6)
  400         CONTINUE
              WRITE (1,500)
  500         FORMAT (//,"ROW ",I6)
  600     CONTINUE
C
C     CALCULATE RANGE ON PIC(I,J) IN ORDER TO DISPLAY IMAGE
  700 IF (IDISP.NE.1) GO TO 900
      PMIN=255
      PMAX=1
      DO 800 I=1,IMAX
      DO 800 J=1,JMAX
          IF (PIC(I,J).LT.PMIN) PMIN=PIC(I,J)
          IF (PIC(I,J).GT.PMAX) PMAX=PIC(I,J)
C         TARGET BLANKING
          IF (IDISP.NE.3) GO TO 800
              PMIN=0
              IF (((I.LT.IPOS1).AND.(I.GT.IPOS2)).AND.((J.LT.JPOS1).AND.
     +        (J.GT.JPOS2))) PIC(I,J)=0
  800 CONTINUE
      CALL DISP(PIC)
C
  900 CONTINUE
C
      RETURN
C
C
      END

**  NO ERRORS**     PROGRAM = [illegible]      COMMON = [illegible]24

          PAGE 0043  UTIL    FTN4 COMPILER: HP24177  (SEPT. 1974)

      ENDS
      FTN4,L
C
C
      SUBROUTINE SORT(PIC,MEAN)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                        CC
CC                                                                        CC
CC    THE PURPOSE OF THIS ROUTINE IS TO REPACK THE INTEGER DATA           CC
CC    ARRAY IN A MANNER WHICH PHYSICALLY RESEMBLES THE REAL WORLD.        CC
CC    THIS IS NECESSARY BECAUSE THE CAMERA'S DIGITAL DATA MAY NOT         CC
CC    MATCH THE FIXED FORTRAN ARRAY DIMENSIONS. THE ARRAY IS REPACKED     CC
CC    INTO ITSELF DUE TO THIS OPERATING SYSTEM'S MEMORY LIMITATIONS.      CC
CC                                                                        CC
CC    SOURCE FILE:            SORS                                        CC
CC    OBJECT FILE:            SORR                                        CC
CC    CALLED BY:              MAIN                                        CC
CC                                                                        CC
CC    PIC                     INTEGER DATA ARRAY                          CC
CC    IMAX                    NUMBER OF SAMPLES IN X DIMENSION            CC
CC    JMAX                    NUMBER OF SAMPLES IN Y DIMENSION            CC
CC    ICOUNT                  TOTAL NUMBER OF SAMPLES                     CC
CC    IPOS & JPOS             POINTERS TO THE LOCATION OF NEXT ELEMENT    CC
CC    I & J                   DO LOOP CONTROL VARIABLES                   CC
CC    MEAN                    MEAN INTENSITY OF DATA ARRAY                CC
CC                                                                        CC
CC                                                                        CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      INTEGER JPOS1,JPOS2,IODEV,IDISP,IVIEW,IOPT,IMOVE,PMAG,I0,J0
      INTEGER ISTEP1,ISTEP2,IDIR,POS1,POS2,IPOS,JPOS,I,J,PIC(100,100)
      REAL MEAN
      COMMON ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      COMMON JPOS1,JPOS2,IODEV,IDISP,IVIEW,IOPT,IMOVE,PMAG,I0,J0
      COMMON ISTEP1,ISTEP2,IDIR,POS1,POS2
C
      MEAN=0
C
C     SET POINTERS TO LAST ELEMENT IN EXISTING ARRAY
      IPOS=ICOUNT/100+1
      JPOS=ICOUNT-100*(IPOS-1)
C     IF ROW POINTER EQUALS ZERO THEN RESET IT TO 100 AND DECREMENT
C     COLUMN POINTER
      IF (JPOS.GT.0) GO TO 100
          JPOS=100
          IPOS=IPOS-1
  100 CONTINUE
C
C     BEGIN REPACKING FROM LAST ELEMENT
      DO 200 J=JMAX,1,-1
      DO 200 I=IMAX,1,-1
```

```
          MEAN=MEAN+FLOAT(PIC(I,J)/ICOUNT)
          PIC(I,J)=PIC(JPOS,IPOS)
C         DECREMENT ROW POINTER
          JPOS=JPOS-1
```

```
C          IF ROW POINTER EQUALS ZERO THEN RESET IT TO 100 AND
C          DECREMENT THE COLUMN POINTER
           IF (JPOS.GT.0) GO TO 200
               JPOS=100
               IPOS=IPOS-1
C
  200    CONTINUE
C
         RETURN
C
C
         END

** NO ERRORS**    PROGRAM = 00124      COMMON = 00024

         PAGE 0003  SORT    FTN4 COMPILER: HP24177 (SEPT. 1974)

         ENDS
```

```
      FTN4,L
C
C
      SUBROUTINE RECT(PIC)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                      CC
CC                                                                      CC
CC    THE PURPOSE OF THIS ROUTINE IS TO PERFORM TARGET SELECTION        CC
CC    AND SEGMENTATION ON THE BASIS THAT THE TARGET INTENSITY DIFFERS   CC
CC    FROM THAT OF THE BACKROUND. ROW AND COLUMN SUMS ARE CREATED       CC
CC    FROM THE INTEGER DATA ARRAY AND EACH ARE EXAMINED FOR THE TWO     CC
CC    GREATEST DIFFERENCES WHICH INDICATE THE POSITIONS WHERE THERE     CC
CC    IS THE GREATEST TRANSITION FROM BACKROUND TO TARGET. WITH THESE   CC
CC    BOUNDS ON THE HORIZONTAL AND VERTICAL OF THE TARGET, 20 DATA      CC
CC    POINTS ARE SELECTED IN THE CENTERMOST PORTION OF THE ESTIMATED    CC
CC    TARGET REGION. THIS ALGORITHM ASSUMES A FAIRLY EVEN BACKROUND     CC
CC    AND THAT THE TARGET HAS FAIRLY EQUAL DIMENSIONS.                  CC
CC                                                                      CC
CC    SOURCE FILE:               RECS                                   CC
CC    OBJECT  FILE:              RECR                                   CC
CC    CALLED BY:                 MAIN                                   CC
CC                                                                      CC
CC    THIS PROGRAM CALLS THE FOLLOWING ROUTINES:                        CC
CC        ZER                    TO INITIALIZE ARRAYS TO ZERO           CC
CC        SUM                    EXAMINES ROW AND COLUMN SUMS           CC
CC        LOC                    TO ORDER TARGET POSTION PARAMETERS AND CC
CC                               SELECT THE CENTERMOST TARGET REGION    CC
CC                                                                      CC
CC    PIC                        INTEGER DATA ARRAY                     CC
CC    IMAX                       NUMBER OF SAMPLES IN THE X DIMENSION   CC
CC    JMAX                       NUMBER OF SAMPLES IN THE Y DIMENSION   CC
CC    ISUM & JSUM                ROW AND COLUMN SUMMING VECTORS         CC
CC    IPOS1 & IPOS2              TARGET BOUNDARIES IN X DIMENSION       CC
CC    JPOS1 & JPOS2              TARGET BOUNDARIES IN Y DIMENSION       CC
CC    I & J                      DO LOOP CONTROL VARIABLES              CC
CC                                                                      CC
CC                                                                      CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      INTEGER JPOS1,JPOS2,IPREV,IDISP,IVIEW,IDOPT,IMOVE,RMAG,IC,JC
      INTEGER ISTEP,ISTEP2,IDIR,POS1,POS2,I,J,ISUM(100),JSUM(100)
      INTEGER PIC(100,100)
      COMMON ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      COMMON JPOS1,JPOS2,IPREV,IDISP,IVIEW,IDOPT,IMOVE,RMAG,IC,JC
      COMMON ISTEP,ISTEP2,IDIR,POS1,POS2
C
C
C     INITIALIZE ARRAYS
      CALL ZER(ISUM,IMAX,1)
      CALL ZER(JSUM,JMAX,1)
```

```
C
C     CREATE ROW SUM
      DO 100 I=1,IMAX
      DO 100 J=1,JMAX
         ISUM(I)=ISUM(I)+PIC(I,J)
  100 CONTINUE
C
C     CREATE COLUMN SUM
      DO 200 J=1,JMAX
      DO 200 I=1,IMAX
         JSUM(J)=JSUM(J)+PIC(I,J)
  200 CONTINUE
C
C     EXAMINE ROW AND COLUMN VECTORS FOR THEIR TWO GREATEST DIFFERENCES
      CALL SUM(ISUM,IMAX,IPOS1,IPOS2)
      CALL SUM(JSUM,JMAX,JPOS1,JPOS2)
C
C     SELECT COORDINATES OF 20 INNERMOST DATA POINTS
      CALL LOC
C
      RETURN
C
C
      END

**  NO ERRORS**     PROGRAM = 00315      COMMON = 00024

        PAGE  0002  RECT    FTN4 COMPILER: HP24177  (SEPT. 1974)

      END$
```

```
PAGE 0001           FTN4 COMPILER: HP24177  (SEPT. 1974)
      FTN4,L
C
C
      SUBROUTINE SUM(VECT,N,POS1,POS2)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                      CC
CC                                                                      CC
CC    THE PURPOSE OF THIS ROUTINE IS TO EXAMINE THE VECTOR CONTAINING  CC
CC    THE SUMMATIONS AND DETERMINE THE LOCATIONS OF THE TWO LARGEST    CC
CC    DIFFERENCES BETWEEN THE SUMS VECT(I) AND VECT(I-1).              CC
CC                                                                      CC
CC    SOURCE FILE:            SUMS                                      CC
CC    OBJECT FILE:            SUMR                                      CC
CC    CALLED BY:              RECT                                      CC
CC                                                                      CC
CC    VECT                    VECTOR CONTAINING SUMMATIONS              CC
CC    N                       NUMBEROF ELEMENTS IN THE VECTOR           CC
CC    POS1 & POS2             POINTERS TO THE TWO GREATEST DIFFERENCES CC
CC    GRAD1 & GRAD2           VALUES OF THE TWO GREATEST DIFFERENCES   CC
CC    GARD3                   VALUE OF THE CURRENT DIFFERENCE          CC
CC    I                       DO LOOP CONTROL VARIABLE                 CC
CC                                                                      CC
CC                                                                      CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER VECT(144),POS1,POS2,I,J,K,M,N,P,GRAD1,GRAD2,GRAD3
C
C
C     INITIALIZE POINTERS
      POS1=9
      POS2=1
C
C     INITIALIZE GRAD1 & GRAD2 TO THE FIRST DIFFERENCE
      GRAD1=IABS(VECT(1)-VECT(2))
      GRAD2=GRAD1
C
C     EXAMINE THE REMAINING DIFFERENCES
      DO 200 I=3,N
C
          GRAD3=IABS(VECT(I)-VECT(I-1))
C
C         CURRENT DIFFERENCE IS GREATER THAN LARGEST DIFFERENCE
C         STORE GREATEST DIFFERENCE IN NEXT GREATEST DIFFERENCE
C         STORE CURRENT DIFFERENCE IN GREATEST DIFFERENCE AND IN
C         A LIKEWISE MANNER ADJUST THE LOCATIONS OF THE DIFFERENCES
          IF (GRAD3.LE.GRAD1) GO TO 100
              GRAD2=GRAD1
              GRAD1=GRAD3
              POS2=POS1
              POS1=I
              GO TO 200

PAGE 0002 SUM       FTN4 COMPILER: HP24177  (SEPT. 1974)
```

```
C          CURRENT DIFFERENCE IS GREATER THAN SECOND LARGEST DIFFERENCE
C          STORE NEW SECOND GREATEST DIFFERENCE AND POSITION
    100    IF (GRAD3.LE.GRAD2) GO TO 200
               GRAD2=GRAD3
               POS2=I
C
    200  CONTINUE
C
         RETURN
C
C
         END
** NO ERRORS**     PROGRAM = 00385       COMMON = 00000

         PAGE  0003  SUB     FTN4 COMPILER: HP24177  (SEPT. 1974)

         END$
```

```
      FTN4,L
C
C
      SUBROUTINE LOC
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC
CC
CC    THE PURPOSE OF THIS ROUTINE IS TO ORDER THE TARGET COORDINATES
CC    IN EACH DIMENSION FROM LARGEST TO SMALLEST AND TO DETERMINE
CC    THE 2ND INNERMOST DATA POINTS.
CC
CC    SOURCE FILE:               LOCS
CC    OBJECT FILE:               LOCR
CC    CALLED BY:                 RECT
CC
CC    IPOS1 & IPOS2              TARGET BOUNDARIES IN X DIMENSION
CC    JPOS1 & JPOS2              TARGET BOUNDARIES IN Y DIMENSION
CC    ITEMP & JTEMP              TEMPORARY STORAGE VARIABLES
CC    INUM  & JNUM               NUMBER OF SAMPLES IN X & Y DIMENSIONS
CC    IPROD                      TOTAL NUMBER OF SAMPLES
CC    SCALE                      SIZE ADJUSTMENT FACTOR
CC
CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      INTEGER JPOS1,JPOS2,IOCEV,IDISP,IVIEW,IDOPT,IMOVE,PMAG,ID,JD
      INTEGER ISTEP1,ISTEP2,IDIR,POS1,POS2,ITEMP,JTEMP,INUM,JNUM,IPROD
      REAL SCALE
      COMMON ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      COMMON JPOS1,JPOS2,IOCEV,IDISP,IVIEW,IDOPT,IMOVE,PMAG,ID,JD
      COMMON ISTEP1,ISTEP2,IDIR,POS1,POS2
C
C
C     ORDER IPOS1 AND IPOS2 (IPOS1>IPOS2)
      IF (IPOS1.GT.IPOS2) GO TO 100
          ITEMP=IPOS1
          IPOS1=IPOS2
          IPOS2=ITEMP
C
C     ORDER JPOS1 AND JPOS2 (JPOS1>JPOS2)
  100 IF (JPOS1.GT.JPOS2) GO TO 200
          JTEMP=JPOS1
          JPOS1=JPOS2
          JPOS2=JTEMP
C
C     CALCULATE MIDPOINTS
  200 ITEMP=(IPOS1+IPOS2)/2
      JTEMP=(JPOS1+JPOS2)/2
C
C
```

```
C     CALCULATE NUMBER OF POINTS IN EACH DIMENSION
      INUM=IPOS1-IPOS2+1
      JNUM=JPOS1-JPOS2+1
```

```
              IPROD=INUM*JNUM
              SCALE=SQRT(IPROD/20.0)
      C
      C       RETURN IF TOTAL NUMBER OF POINTS IS LESS THAN 20
              IF (IPROD.LE.20) GO TO 500
      C
      C       ADJUST NUMBER OF POINTS IN EACH DIMENSION BY SCALE FACTOR
              INUM=INT(INUM/SCALE)
              JNUM=INT(JNUM/SCALE)
      C
      C       CHECK SPECIAL CASE: INUM=0 OR JNUM=0
                 IF (INUM.NE.0) GO TO 300
                      INUM=1
                      JNUM=20
        300      IF (JNUM.NE.0) GO TO 400
                      JNUM=1
                      INUM=20
      C
      C         COMPUTE NEW POSITONS
        400     IPOS1=ITEMP+INUM/2
                IPOS2=ITEMP-INUM/2
                JPOS1=JTEMP+JNUM/2
                JPOS2=JTEMP-JNUM/2
      C
        500     RETURN
      C
      C
                END

** NO ERRORS**     PROGRAM = 00157       COMMON = 00024

         PAGE  0003  LOC      FTN4 COMPILER: HP24177  (SEPT. 1974)

   $            ENDS
```

```
      PAGE 0001           FTN4 COMPILER: HP24177  (SEPT. 1974)

      FTN4,L
C
C
      SUBROUTINE DLOAD(PIC,D)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                      CC
CC                                                                      CC
CC    THE PURPOSE OF THIS ROUTINE IS TO CREATE A SCENE VECTOR THAT      CC
CC    CONTAINS THE POINTS WITHIN THE BOUNDARIES AS SPECIFIED BY         CC
CC    THE TARGET LOCATION IN THE INITAL SCENE. THIS VECTOR WILL         CC
CC    LATER BE USED IN CALCULATING THE SCENE DIFFERNECE VECTOR.         CC
CC                                                                      CC
CC    SOURCE FILE:               DLOAS                                  CC
CC    OBJECT FILE:               DLOAR                                  CC
CC    CALLED BY:                 MAIN                                   CC
CC                                                                      CC
CC    PIC                        INTEGER DATA ARRAY                     CC
CC    IPOS1 & IPOS2              TARGET COORDINATES IN X DIMENSION      CC
CC    JPOS1 & JPOS2              TARGET COORDINATES IN Y DIMENSION      CC
CC    D                          VECTOR CONTAINING POINTS INTERIOR      CC
CC                               TO INITAL SCENE TARGET LOCATION        CC
CC    K                          TOTAL NUMBER OF POINTS                 CC
CC    I & J                      DO LOOP CONTROL VARIABLES              CC
CC                                                                      CC
CC                                                                      CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      INTEGER JPOS1,JPOS2,IODEV,IDISP,IVIEW,IOPT,IMOVE,PMAG,IO,JO
      INTEGER ISTEP,ISTEP2,IDIR,POS1,POS2,I,J,K,PIC(100,100)
      REAL D(20)
      COMMON ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      COMMON JPOS1,JPOS2,IODEV,IDISP,IVIEW,IOPT,IMOVE,PMAG,IO,JO
      COMMON ISTEP,ISTEP2,IDIR,POS1,POS2
C
C
C     STORE DATA POINTS IN D VECTOR
      K=0
      DO 100 I=IPOS2,IPOS1
      DO 100 J=JPOS2,JPOS1
         K=K+1
          D(K)=FLOAT(PIC(I,J))
  100 CONTINUE
C
      RETURN
C
C
      END

** NO ERRORS**      PROGRAM = 00059        COMMON = 00024

      PAGE 0002   DLOAD    FTN4 COMPILER: HP24177  (SEPT. 1974)
```

```
      PAGE 0001        FTN4 COMPILER: HP24177  (SEPT. 1974)

            FTN4,L
      C
      C
            SUBROUTINE DISP(IPIX)
      C
      C
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CC                                                                    CC
      CC                                                                    CC
      CC    THE PURPOSE OF THIS ROUTINE IS TO DISPLAY AN IMAGE OF THE       CC
      CC    INTEGER DATA ARRAY ON THE TEKTRONIX 4014 TERMINAL WITH          CC
      CC    ENHANCED GRAPHICS.                                              CC
      CC                                                                    CC
      CC    SOURCE FILE:             DISPS                                  CC
      CC    OBJECT FILE:             DISPR                                  CC
      CC    CALLED BY:               MAIN                                   CC
      CC                                                                    CC
      CC    PMIN                     MINIMUM INTEGER VALUE TO BE DISPLAYED  CC
      CC    PMAX                     MAXIMUM INTEGER VALUE TO BE DISPLAYED  CC
      CC    IMAX                     NUMBER OF SAMPLES IN X DIMENSION       CC
      CC    M                        NUMBER OF SAMPLES IN X DIMENSION       CC
      CC    N                        NUMBER OF SAMPLES IN Y DIMENSION       CC
      CC    PMAG                     MAGNIFICATION FACTOR                   CC
      CC    I0 & J0                  COORDINATES OF IMAGE ON DISPLAY        CC
      CC    IPIX                     INTEGER DATA ARRAY                     CC
      CC                                                                    CC
      CC                                                                    CC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      C
      C
            INTEGER ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
            INTEGER JPOS1,JPOS2,IODEV,IDISP,IVIEW,IDOPT,IMOVE,PMAG,I0,J0
            INTEGER ISTEP1,ISTEP2,IDIR,POS1,POS2,IPIX(100,100),GRAY(15)
            COMMON ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
            COMMON JPOS1,JPOS2,IODEV,IDISP,IVIEW,IDOPT,IMOVE,PMAG,I0,J0
            COMMON ISTEP1,ISTEP2,IDIR,POS1,POS2
            DATA GRAY/16384,16640,16896,17408,17920,18432,18944,19456,19968,
           120736,21760,23040,8192,19752,16128/
      C
      C     INITIALIZE TERMINAL FOR ENHANCED GRAPHICS MODE
            WRITE (IODEV,1) 6912,3072,6912,7168,24320
       1    FORMAT (5A1)
      C
      C     CHECK CONTROL VARIABLES ARE IN THEIR PROPER RANGE: IF NOT
      C     THEN USE DEFAULT VALUES
            IF(PMAG.LE.0.) PMAG=1.
            IF(I0.LE.0.OR.I0.GE.1024) I0=1
            IF(J0.LE.0.OR.J0.GE.1024) J0=1
      C
      C     VERIFY SIZE OF DISPLAYED IMAGE IS LESS THAN 1024 (TERMINAL LIMITS)
            I = M*PMAG+I0-1
            IM=MIN0(I ,1023)-1
            JM = N*PMAG+J0-1
            J = MIN0(JM,1024)-1

      PAGE 0002  DISP    FTN4 COMPILER: HP24177  (SEPT. 1974)

      C
      DO 1000 J=J0,JM,2
      JL=(MOD((JM+J0-J+1),32)+96)*256
      JH=((JM+J0-J+1)/32+32)*256
      DO 1000 I=I0,IM,2
      IL=(MOD((I-1),32)+64)*256
      IH=((I-1)/32+32)*256
      IN=(I-I0)/PMAG+1
      JN=(J-J0)/PMAG+1
      IP=(IPIX(IN,JN)-PMIN)*16/(PMAX-PMIN+1)
      IF(IP.GT.15) IP=15
      IF(IP.LE.0) GOTO 1000
      WRITE (15,1) GRAY(IP),JH,JL,IH,IL,24320
 1000 CONTINUE
C
      WRITE(15,1) 7936
C
      RETURN
C
C
      END

** NO ERRORS**    PROGRAM = 00349      COMMON = 00024

        PAGE 0003  DISP    FTN4 COMPILER: HP24177  (SEPT. 1974)

      ENDS
      FTN4,L
C
C
      SUBROUTINE DERV(PIC,D,PD,K)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                       CC
CC                                                                       CC
CC    THE PURPOSE OF THIS ROUTINE IS TO CALCULATE THE WEIGHTED AND       CC
CC    UNWEIGHTED SPATIAL DERRIVATIVES OF A PORTION OF AN INTEGER         CC
CC    DATA ARRAY FOR USE WITH THE INTERACTIVE VIDEO TRACKING SOFTWARE CC
CC    SYSTEM.                                                            CC
CC                                                                       CC
CC    SOURCE FILE:            DERS                                       CC
CC    OBJECT FILE:            DERB                                       CC
CC    CALLED BY:              MAIN                                       CC
CC                                                                       CC
CC    PIC                     INTEGER DATA ARRAY                         CC
CC    IPOS1 & IPOS2           TARGET BOUNDARIES IN X DIMENSION           CC
CC    JPOS1 & JPOS2           TARGET BOUNDARIES IN Y DIMENSION           CC
CC    D                       ARRAY OF UNWEIGHTED SPATIAL DERRIVATIVES CC
CC    PD                      ARRAY OF WEIGHTED SPATIAL DERRIVATIVES     CC
CC    IDOPT                   DERRIVATIVE CALCULATION OPTION             CC
CC    IVIEW                   DERRIVATIVE DISPLAY OPTION                 CC
CC    I1 - I7                 POINTERS USED IN DERRIVATIVE CALCULATION CC
CC    IORG & JORG             IMAGE PLANE ORIGIN COORDINATES            CC
CC    I & J                   DO LOOP CONTROL VARIABLES                  CC
CC    K                       TOTAL NUMBER OF DERRIVATIVES              CC
CC                                                                       CC
CC                                                                       CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      INTEGER JPOS1,JPOS2,IOLEV,IDISP,IVIEW,IDOPT,IMOVE,PMAG,I0,J0
      INTEGER ISTEP1,ISTEP2,INIR,POS1,POS2,I1,I2,I3,I4,I5,I6,I7,I,J
      INTEGER PIC(100,100),K,IORG,JORG
      REAL PD(20,2),D(20,2)
      COMMON ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      COMMON JPOS1,JPOS2,IOLEV,IDISP,IVIEW,IDOPT,IMOVE,PMAG,I0,J0
      COMMON ISTEP1,ISTEP2,INIR,POS1,POS2
C
C
C     THE CENTROID OF THE TARGET IN THE ORIGINAL SCENE CAN BE ESTIMATED
C     BY ([IPOS2+(IPOS1-IPOS2)/2],[JPOS2+(JPOS1-JPOS2)/2]). THIS SERVES
C     AS THE ORIGIN OF THE IMAGE PLANE COORDINATE SYSTEM. NOTE THAT THE
C     EXECUTION OF THIS ROUTINE ESTABLISHES A NEW IMAGE ORIGIN.
      IORG=IPOS2+(IPOS1-IPOS2)/2
      JORG=JPOS2+(JPOS1-JPOS2)/2
C
C
      K=0
      DO 20 I=IPOS2,IPOS1
```

```
      DO 30 J=JPOS2,JPOS1
C
C     DERRIVATIVE USING THE I+1 AND I POINTS
```

```
            I1=I+1
            I2=J
            I3=I
            I4=I
            I5=J+1
            I6=J
            I7=1
            GO TO 200
C
C           DERIVATIVE USING THE I+1 AND I-1 POINTS
     1[illegible]  I1=I+1
            I2=J
            I3=I-1
            I4=I
            I5=J+1
            I6=J-1
            I7=2
C
C           LOAD THE ARRAYS
  200       K=K+1
            G(K,1)=FLOAT(PIC(I1,I2)-PIC(I3,I2))/I7
            G(K,2)=FLOAT(PIC(I4,I5)-PIC(I4,I6))/I7
            PC(K,1)=(I-IORG)*G(K,1)+(J-JORG)*G(K,2)
            PC(K,2)=(I-IORG)*G(K,2)-(J-JORG)*G(K,1)
C
  300  CONTINUE
C
C
       IF (IWIT .NE.1) GO TO 700
C
C      OUTPUT DERIVATIVE CALCULATIONS
       WRITE (1,400)
       WRITE (1,500) ((G(I,J),J=1,2),I=1,K)
       WRITE (1,600)
       WRITE (1,500) ((PC(I,J),J=1,2),I=1,K)
  400  FORMAT (///,"G ARRAY",/)
  500  FORMAT (2[illegible])
  600  FORMAT (///,"PC ARRAY",/)
C
  700  RETURN
C
C
       END

**  NO ERRORS**    PROGRAM = [illegible]41[illegible]       COMMON = [illegible]24
         PAGE  0003  DERV     FTN4 COMPILER: HP24177  (SEPT. 1974)

       $
```

```
      FTN4,L
C
C
      SUBROUTINE TRACK(K,FC,G,SCALE,D1,D2,A)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                    CC
CC                                                                    CC
CC    THE PURPOSE OF THIS ROUTINE IS TO SOLVE THE TSVIP ALGORITHM     CC
CC    FOR THE AFFINE PARAMETERS USING THE PSEUDO INVERSE (A = DCT * D)CC
CC                                                                    CC
CC    SOURCE FILE:              TRACS                                 CC
CC    OBJECT FILE:              TRACR                                 CC
CC    CALLED BY:                CONT                                  CC
CC                                                                    CC
CC    THIS PROGRAM CALLS THE FOLLOWING ROUTINES                       CC
CC    PSEUD                     CREATES THE PSEUDO INVERSE OF DC IN DCT  CC
CC    MPY                       CREATES THE PRODUCT OF DCT AND D      CC
CC                                                                    CC
CC    A                         4 X 1  ARRAY CONTAINING THE AFFINE COEFF.CC
CC    DC                        ARRAY COMPOSED OF FC AND G            CC
CC    G                         ARRAY OF UNWEIGHTED SPATIAL DERRIVATIVES CC
CC    FC                        ARRAY OF SPATIAL DERRIVATIVES         CC
CC    K                         NUMBER OF POINTS IN TARGET            CC
CC    I & J                     DO LOOP CONTROL VARIABLES             CC
CC    SCALE                     SCALE FACTOR TO REDUCE SENSITIVITY TO CC
CC                              NOISE                                 CC
CC                                                                    CC
CC                                                                    CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      REAL A(4,1),DC(20,4),DCT(4,20),DUM1(4,20),DUM2(4,20),G(20,2)
      REAL FC(20,2),D1(20),D2(20),D(20)
C
C     SCALE D2 BY THE LIGHT CORRECTION FACTOR
      DO 100 I=1,K
         D2(I)=D2(I)*SCALE
  100 CONTINUE
C
C     COMPUTE SCENE DIFFERENCE VECTOR
      CALL SUB(D2,D1,D,K,1)
C
C     LOAD DC MATRIX   DC = [ FC : G ]
      DO 200 I=1,K
      DO 200 J=1,2
         DC(I,J)=FC(I,J)
         DC(I,J+2)=G(I,J)
  200 CONTINUE
C
C     CALL PSEUDO INVERSE SOLVE FOR THE AFFINE PARAMETERS
      CALL PSEUD(DC,DCT,K,4,DUM1,DUM2)
      CALL MPY(DCT,D,A,4,K,1)
```

```
0058          RETURN
0059   C
0060   C
0061          END

**  NO ERRORS**    PROGRAM = 00815       COMMON = 00000

          PAGE  0003  TRACK   FTN4 COMPILER: HP24177  (SEPT. 1974)

0002          ENDS
```

```
      PAGE 0001          FTN4 COMPILER: HP24177 (SEPT. 1974)

      FTN4,L
C
C
      SUBROUTINE PSEUD(A,APSEUD,M,N,ATRN,B)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC
CC
CC    THE PURPOSE OF THIS ROUTINE IS TO CREATE THE PSEUDO INVERSE
CC    OF A AND STORE IT IN APSEUD. APSEUD = INV(TRN(A)*A)*TRN(A)
CC
CC    SOURCE FILE:             PINS
CC    OBJECT FILE:             PINR
CC    CALLED BY:               MAIN
CC
CC    THIS PROGRAM CALL THE FOLLOWING ROUTINES:
CC        TRN                  CREATES THE TRANSPOSE OF THE GIVEN ARRAY
CC        MPY                  MULTIPLIES TWO ARRAYS
CC        INV                  CREATES THE INVERSE OF A SQUARE ARRAY
CC
CC    A                        PARAMETER ARRAY: DIM. M X N
CC    ATRN                     TRANSPOSE OF ARRAY A: DIM. N X M
CC    APSEUD                   PSEUDOINVERSE OF ARRAY A: DIM. N X M
CC    B                        PRODUCT OF MATRICES ATRN AND A:
CC                             DUMMY STORAGE ARRAY: DIM. N X N
CC    M & N                    DIMENSIONS OF THE ARRAYS SPECIFIED ABOVE
CC
CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER M,N
      REAL A(M,N),ATRN(N,M),APSEUD(N,M),B(N,N)
C
C
C     CREATE TRANSPOSE OF A MATRIX
      CALL TRN(A,ATRN,M,N)
C
C     MULTIPLY THE TRANSPOSE OF A BY A AND STORE THE RESULT IN B
      CALL MPY(ATRN,A,B,N,M,N)
C
C
C     STORE INVERSE OF B IN B
      CALL INV(B,N,N,IFAIL)
C
C     INVERSE DOES NOT EXIST DETECT ERROR
      IF (IFAIL.NE.1) GO TO 200
      WRITE(1,100)
  100 FORMAT("NON-EXISTENT INVERSE")
      STOP
C
C     MULTIPLY B BY THE TRANSPOSE OF A AND STORE RESULT IN APSEUD
  200 CALL MPY(B,ATRN,APSEUD,N,N,M)

      PAGE 0002  PSEUD   FTN4 COMPILER: HP24177 (SEPT. 1974)

C
```

```
0060  C
0061          END

**  NO ERRORS**    PROGRAM = 00078       COMMON = 00000

         PAGE  0003  PSEUD   FTN4 COMPILER: HP24177  (SEPT. 1974)

0062          END$
```

```
      FTN4,L
C
C
      SUBROUTINE INV(A,IA,N,IFAIL)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                       CC
CC                                                                       CC
CC    THE PURPOSE OF THIS ROUTINE IS TO FIND THE INVERSE OF A MATRIX     CC
CC    BY GAUSS-JORDAN ELIMINATION. APPLYING TO THE ROWS OF THE           CC
CC    IDENTITY MATRIX I THE SAME ELEMENTARY ROW TRANSFORMATIONS AS       CC
CC    THOSE BY WHICH A IS REDUCED TO THE CANONICAL FORM I, THE           CC
CC    INVERSE OF A IS OBTAINED. PARTIAL PIVOTING FOR THE LARGEST         CC
CC    DIAGONAL ELEMENT IS ALSO DONE.                                     CC
CC                                                                       CC
CC    SOURCE FILE:              INVS                                     CC
CC    OBJECT FILE:              INVR                                     CC
CC    CALLED BY:                PSEUD                                    CC
CC                                                                       CC
CC    A                         AN N X N INPUT ARRAY WHOSE INVERSE IS    CC
CC                              DESIRED. NOTE A IS DESTROYED BY ITS      CC
CC                              INVERSE.                                 CC
CC    IA                        COLUMN LENGTH OF A                       CC
CC    N                         THE ORDER OF THE SYSTEM                  CC
CC    IROW                      TEMPORARY STORAGE ARRAY OF N WORDS       CC
CC    TEMP                      TEMPORARY STORAGE ARRAY OF N WORDS       CC
CC                                                                       CC
CC                                                                       CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      DIMENSION A(IA,IA),IROW(100),TEMP(100),PI(5)
C
C
      IFAIL=0
      K=N-1
      DO 14 L=1,K
      LM=K-L+1
      AMAX=ABS(A(L,L))
      ISAVE=L
      LMZ=L+1
      DO 18 J=LMZ,N
      IF(ABS(A(J,L)).LE.AMAX) GO TO 18
      AMAX=ABS(A(J,L))
      ISAVE=J
   18 CONTINUE
      IF (AMAX.EQ.0) GO TO 100
      IROW(L)=ISAVE
      DO 20 M=1,N
      X=A(L,M)
      A(L,M)=A(ISAVE,M)
   20 A(ISAVE,M)=X
      DO 14 I=1,LM
```

```
            LS=I+L
            A(LS,L)=-A(LS,L)/A(L,L)
            DO 14 II=1,K
            LT=II+1
            IF (LT.GT.L) GO TO 14
            LT=LT-1
      14    A(LS,LT)=A(LS,LT)+A(LS,L)*A(L,LT)
            IF (A(M,M).EQ.0) GO TO 100
            DO 64 I=1,K
      64    A(M,I)=A(M,I)/A(M,M)
            A(M,M)=1.0/A(M,M)
            DO 32 L=1,K
            LM=K-L+1
            LLL=L+1
            DO 24 J=1,LLL
            LT=M-J+1
            TEMP(J)=A(LM,LT)
            A(LM,LT)=0.0
            IF(J.EQ.LLL) A(LM,LT)=1.0
      24    CONTINUE
            DO 30 N=1,L
            M2=M-N+1
            DO 30 M1=1,M
            LZ=M-M1+1
      30    A(LM,LZ)=A(LM,LZ)-TEMP(N)*A(M2,LZ)
            DO 32 III=1,M
      32    A(LM,III)=A(LM,III)/TEMP(L+1)
            DO 50 I=1,K
            LM=K-I+1
            IF (IROW(LM).EQ.LM) GO TO 50
            M1=IROW(LM)
            DO 52 J=1,M
            X=A(J,LM)
            A(J,LM)=A(J,M1)
      52    A(J,M1)=X
      50    CONTINUE
            RETURN
      100   IFAIL=1
            RETURN
            END

** NO ERRORS**     PROGRAM = 00966       COMMON = 00000

         PAGE 0003  INV      FTN4 COMPILER: HP24177  (SEPT. 1974)

            END$
```

```
          PAGE  0001          FTN4 COMPILER: HP24177  (SEPT. 1974)

              FTN4,L
       C
       C
              SUBROUTINE PERT(I1,IMAX,JMAX)
       C
       C
       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
       CC                                                                   CC
       CC                                                                   CC
       CC     THE PURPOSE OF THIS ROUTINE IS TO SIMULATE TARGET MOTION BY   CC
       CC     THE DATA ARRAY                                                CC
       CC                                                                   CC
       CC     SOURCE FILE:             PERTS                                CC
       CC     OBJECT FILE:             PERTR                                CC
       CC     CALLED BY:               CONT                                 CC
       CC                                                                   CC
       CC     I1                       IMAGE DATA ARRAY                     CC
       CC     IMAX & JMAX              DIMENSIONS OF DATA ARRAY             CC
       CC     ISHIFT & JSHIFT          SHIFT FACTORS                        CC
       CC     IPTR & JPTR              LOCATION INDICES                     CC
       CC                                                                   CC
       CC                                                                   CC
       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
       C
       C
              INTEGER I1(120,100)
       C
              WRITE (1,100)
        100   FORMAT ("INPUT HORIZONTAL AND VERTICAL PERTURBATIONS")
              READ (1,*) ISHIFT,JSHIFT
       C
              DO 300 I=1,IMAX
              DO 300 J=1,JMAX
              IPTR=ISHIFT+I
              JPTR=JSHIFT+J
              IF (((IPTR.LT.1).OR.(IPTR.GT.IMAX)).OR.((JPTR.LT.1).OR.(JPTR.GT.
             +JMAX))) GO TO 300
              I1(I,J)=I1(IPTR,JPTR)
        300   CONTINUE
       C
              RETURN
       C
       C
              END

 **  NO ERRORS**     PROGRAM = 00126       COMMON = 00000

          PAGE  0002  PERT    FTN4 COMPILER: HP24177  (SEPT. 1974)

              ENDS
          PAGE  0001          FTN4 COMPILER: HP24177  (SEPT. 1974)

      FTN4,L
C
C
      SUBROUTINE PANT(B1,B2)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                    CC
CC                                                                    CC
CC    THE PURPOSE OF THIS ROUTINE IS TO ALTER THE CAMERA POSITION     CC
CC    TO COMPENSATE FOR TARGET MOTION. THE SIGN OF THE AFFFINE        CC
CC    ESTIMATES ARE EXAMINED TO DETERMINE THE DIRECTION OF THE MOTION CC
CC                                                                    CC
CC    SOURCE FILE:              PANTS                                 CC
CC    OBJECT FILE:              PANTR                                 CC
CC    CALLED BY:                CONT                                  CC
CC                                                                    CC
CC    THIS PROGRAM CALLS THE FOLLOWING ROUTINES:                      CC
CC        MOTOR                 DRIVER FOR THE PAN TILT MOUNT         CC
CC                                                                    CC
CC    B1 & B2                   AFFINE ESTIMATES                      CC
CC    ISTEP1 & ISTEP2           CAMERA MOVEMENT                       CC
CC    JSTEP1 & JSTEP2           TEMPORARTY STORAGE                    CC
CC    IPER                      PAN TILT SPEED CONTROL                CC
CC    IDIR                      PAN TILT DIRECTION CONTROL            CC
CC                                                                    CC
CC                                                                    CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      JSTEP1=1
      JSTEP2=1
      IF (B1.EQ.0) JSTEP1=0
      IF (B2.EQ.0) JSTEP2=0
      IPER=3
      B1=-B1
      B2=-B2
      IF ((B1.LT.0).AND.(B2.LT.0)) IDIR=1
      IF ((B1.LT.0).AND.(B2.GE.0)) IDIR=3
      IF ((B1.GE.0).AND.(B2.GE.0)) IDIR=2
      IF ((B1.GE.0).AND.(B2.LT.0)) IDIR=4
      WRITE(1,1000) IDIR
 1000 FORMAT("DIRECTION",I6)
      CALL MOTOR(12,ISTEP1,ISTEP2,IDIR,IPER)
      POS1=POS1+SIGN(JSTEP1,B1)
      POS2=POS2+SIGN(JSTEP2,B2)
C
      RETURN
C
C
      END

 ** NO ERRORS**    PROGRAM = 00206      COMMON = 00000

          PAGE  0002  PANT    FTN4 COMPILER: HP24177  (SEPT. 1974)

      END$
      FTN4,L
C
C
      SUBROUTINE DRIVE
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                      CC
CC                                                                      CC
CC    THE PURPOSE OF THIS ROUTINE IS TO ALLOW THE OPERATOR TO MOVE OR   CC
CC    POSITION THE CAMERA SENSOR SOME SPECIFIED AMOUNT.                 CC
CC                                                                      CC
CC    SOURCE FILE:              DRIVS                                   CC
CC    OBJECT FILE:              DRIVR                                   CC
CC    CALLED BY:                CONT                                    CC
CC                                                                      CC
CC    THIS PROGRAM CALLS THE FOLLOWING ROUTINES:                        CC
CC         MOTOR                ASSEMBLY LANGUAGE DRIVER FOR PANT TILT  CC
CC                              MOUNT                                   CC
CC                                                                      CC
CC    ISTEP1                    NUMBER OF MOTOR STEPS IN Y DIMENSION    CC
CC                              1 STEP = Ø.Ø3 DEGREES                   CC
CC    ISTEP2                    NUMBER OF MOTOR STEPS IN X DIMENSION    CC
CC                              1 STEP = Ø.Ø6 DEGREES                   CC
CC    IDIR                      DIRECTION OF ROTATION                   CC
CC                              Ø    CCW TILT: CCW PAN                  CC
CC                              1    CW TILT: CCW PAN                   CC
CC                              2    CCW TILT: CW PAN                   CC
CC                              3    CW TILT: CW PAN                    CC
CC    IPER                      MOTOR SPEED: 1 LOW: 2 MEDIUM: 3 HIGH    CC
CC    POS1 & POS2               CURRENT CAMERA POSITION                 CC
CC                                                                      CC
CC                                                                      CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      INTEGER JPOS1,JPOS2,IODEV,IDISP,IVIEW,IDOPT,IMOVE,PMAG,IØ,JØ
      INTEGER ISTEP1,ISTEP2,IDIR,POS1,POS2
      COMMON ISTART,JSTART,ISTOP,JSTOP,ICOUNT,IMAX,JMAX,IPOS1,IPOS2
      COMMON JPOS1,JPOS2,IODEV,IDISP,IVIEW,IDOPT,IMOVE,PMAG,IØ,JØ
      COMMON ISTEP1,ISTEP2,IDIR,POS1,POS2
C
C
C     INITIALIZE PAN TILT PARAMETERS
      WRITE(1,1Ø)
  1Ø  FORMAT("ENTER #STEPS FOR PAN AND TILT AND DIRECTION")
      READ(1,*) ISTEP1,ISTEP2,IDIR
      IPER=3
C
C     CALL DRIVER TO MOVE PAN TILT
      CALL MOTOR(12,ISTEP1,ISTEP2,IDIR,IPER)
C
C     CALCULATE NEW CAMERA POSITION
```

120

```
      IF ((IDIR.EQ.Ø).OR.(IDIR.EQ.2)) ISTEP1=-ISTEP1
      IF ((IDIR.EQ.1).OR.(IDIR.EQ.3)) ISTEP2=-ISTEP2
```

```
0060         POS2=POS2+ISTEP2
0061   C
0062         RETURN
0063   C
0064   C
0065         END

**  NO ERRORS**    PROGRAM = 00102       COMMON = 00024

          PAGE  0003  DRIVE   FTN4 COMPILER: HP24177  (SEPT. 1974)

0066         ENDS
```

```
PAGE 0001

                         ASMB,L,R,T
CAS    R 000006
.ENTR  X 000001
PAR    R 000000
ORBIT  R 000061
IODEV  R 000062
MASK   R 000063
XSTRT  R 000064
YSTRT  R 000065
YSTOP  R 000066
OUT      000032
**  NO ERRORS*

 PAGE 0002 #01

                             ASMB,L,R,T
     00000                        NAM   CAS,7
                                  ENT   CAS
                                  EXT   .ENTR

     00000 000000      PAR        BSS   6
     00006 000000      CAS        NOP
     00007 016001X                JSB   .ENTR
     00010 000000R                DEF   PAR
     00011 103100                 CLF   0
     00012 062062R                LDA   IODEV
     00013 102606                 OTA   6
     00014 106702                 CLC   2
     00015 062005R                LDA   PAR+5
     00016 032061R                IOR   ORBIT
     00017 102602                 OTA   2
     00020 102702                 STC   2
     00021 162004R                LDA   PAR+4,I
     00022 003000                 CMA
     00023 002004                 INA
     00024 102602                 OTA   2
     00025 162000R                LDA   PAR,I
     00026 012063R                AND   MASK
     00027 032064R                IOR   XSTRT
     00030 102632                 OTA   OUT
     00031 102732                 STC   OUT
     00032 106732                 CLC   OUT
     00033 162001R                LDA   PAR+1,I
     00034 012063R                AND   MASK
     00035 032065R                IOR   YSTRT
     00036 102632                 OTA   OUT
     00037 102732                 STC   OUT
     00040 106732                 CLC   OUT
     00041 162002R                LDA   PAR+2,I
     00042 102632                 OTA   OUT
     00043 102732                 STC   OUT
     00044 106732                 CLC   OUT
     00045 162003R                LDA   PAR+3,I
     00046 012063R                AND   MASK
     00047 032066R                IOR   YSTOP
     00050 102632                 OTA   OUT
     00051 102732                 STC   OUT
```

```
0044  00054  102300            SFS   0
0045  00055  026054R           JMP   *-1
0046  00056  106700            CLC   0
0047  00057  102100            STF   0
0048  00060  126060R           JMP   CAR,I
0049  00061  100000     OPBIT  OCT   100000
0050  00062  000032     IODEV  OCT   32
0051  00063  000177     MASK   OCT   177
0052  00064  000400     XSTRT  OCT   400
0053  00065  000200     YSTRT  OCT   200
0054  00066  001600     YSTOP  OCT   1600
0055  00032             OUT    EQU   32B
0056                           END

 PAGE 0003 #01

**  NO ERRORS*
```

```
 PAGE 0001

0001                        ASMB,L,R,T
MOTOR R 000005
.ENTR X 000001
PAR   R 000000
PUL1  R 000043
MOTO1 R 000054
ZERO1 R 000072
MOT2  R 000106
PUL2  R 000114
MOTO2 R 000124
ZERO2 R 000142
FIN   R 000156
P1    R 000161
P2    R 000162
P3    R 000163
P4    R 000164
M011  R 000165
M012  R 000166
M021  R 000167
M022  R 000170
ISTE1 R 000171
ISTE2 R 000172
IDIR  R 000173
IPER  R 000174
PER   R 000175
PER1  R 000176
PER2  R 000177
PER3  R 000200
PER12 R 000201
PER22 R 000202
PER32 R 000203
STE1  R 000204
PE2   R 000205
ZE2   R 000206
STE2  R 000207
PE1   R 000210
ZE1   R 000211
LOOP1 R 000212
LOOP2 R 000213
A/D     000016
**  NO ERRORS*

 PAGE 0002 #01
0001                        ASMB,L,R,T
0002  00000                            NAM MOTOR,7
0003                                   ENT MOTOR
0004                                   EXT .ENTR
0005  00000 000000          PAR        BSS 5
0006  00005 000000          MOTOR      NOP
0007  00006 016001X                    JSB .ENTR
0008  00007 000000R                    DEF PAR
0009  00010 103101                     CLF 1
0010  00011 162001R                    LDA PAR+1,I
0011  00012 072171R                    STA ISTE1
0012  00013 042161R                    ADA P1
0013  00014 003000                     CMA
```

```
00017 162007R       LDA PAR+7,I
00020 072174R       STA IPER
00021 052161R       CPA P1
00022 026033R       JMP *+9
00023 052162R       CPA P2
00024 026040R       JMP *+12
00025 062200R       LDA PER3
00026 072212R       STA LOOP1
00027 062203R       LDA PER32
00030 072213R       STA LOOP2
00031 026043R       JMP PUL1
00032 062176R       LDA PER1
00033 072212R       STA LOOP1
00034 062201R       LDA PER12
00035 072213R       STA LOOP2
00036 026043R       JMP PUL1
00037 062177R       LDA PER2
00040 072212R       STA LOOP1
00041 062202R       LDA PER22
00042 072213R       STA LOOP2
00043 162003R PUL1  LDA PAR+3,I
00044 072173R       STA IDIF
00045 012161R       AND P1
00046 052161R       CPA P1
00047 026051R       JMP *+2
00050 026053R       JMP *+3
00051 062165R       LDA GO11
00052 026054R       JMP GOTO1
00053 062166R       LDA GO12
00054 036204R GOTO1 ISZ STE1
00055 026057R       JMP *+2
00056 026106R       JMP GOT2
00057 102616        OTA A/D
00060 062212R       LDA LOOP1
00061 072210R       STA PE1
00062 036210R       ISZ PE1
00063 026065R       JMP *+2
00064 026072R       JMP ZERO1
00065 062213R       LDA LOOP2
00066 072205R       STA PE2
00067 036205R       ISZ PE2

 PAGE 0003 #01
00070 026067R       JMP *-1
00071 026062R       JMP *-7
00072 002400  ZERO1 CLA
00073 102616        OTA A/D
00074 062212R       LDA LOOP1
00075 072211R       STA ZE1
00076 036211R       ISZ ZE1
00077 026101R       JMP *+2
00100 026043R       JMP PUL1
00101 062213R       LDA LOOP2
00102 072206R       STA ZE2
00103 036206R       ISZ ZE2
00104 026103R       JMP *-1
00105 026076R       JMP *-7
00106 162002R GOT2  LDA PAR+2,I
00107 072172R       STA ISTE2
00110 042161R       ADA P1
00111 003000        CMA
00112 002004        INA
00113 072207R       STA STE2
00114 062173R PUL2  LDA IDIF
```

```
0080  00117 024121R         JMP *+2
0081  00120 024123R         JMP *+3
0082  00121 062167R         LDA M021
0083  00122 024124R         JMP MOTO2
0084  00123 062170R         LDA M022
0085  00124 034207R  MOTO2  ISZ STE2
0086  00125 024127R         JMP *+2
0087  00126 024156R         JMP FIN
0088  00127 102616          OTA A/D
0089  00130 062212R         LDA LOOP1
0090  00131 072210R         STA PE1
0091  00132 034210R         ISZ PE1
0092  00133 024135R         JMP *+2
0093  00134 024142R         JMP ZERO2
0094  00135 062213R         LDA LOOP2
0095  00136 072205R         STA PE2
0096  00137 034205R         ISZ PE2
0097  00140 024137R         JMP *-1
0098  00141 024132R         JMP *-7
0099  00142 002400   ZERO2  CLA
0100  00143 102616          OTA A/D
0101  00144 062212R         LDA LOOP1
0102  00145 072211R         STA ZE1
0103  00146 034211R         ISZ ZE1
0104  00147 024151R         JMP *+2
0105  00150 024114R         JMP PUL2
0106  00151 062213R         LDA LOOP2
0107  00152 072206R         STA ZE2
0108  00153 034206R         ISZ ZE2
0109  00154 024153R         JMP *-1
0110  00155 024146R         JMP *-7
0111  00156 062164R  FIN    LDA P4
0112  00157 102100          STF 0

 PAGE 0004 #01

0113  00160 124005R         JMP MOTOR,I
0114  00161 000001   P1     OCT 1
0115  00162 000002   P2     OCT 2
0116  00163 000003   P3     OCT 3
0117  00164 000004   P4     OCT 4
0118  00165 010000   M011   OCT 10000
0119  00166 020000   M012   OCT 20000
0120  00167 040000   M021   OCT 40000
0121  00170 100000   M022   OCT 100000
0122  00171 000000   ISTE1  NOP
0123  00172 000000   ISTE2  NOP
0124  00173 000000   IDIR   NOP
0125  00174 000000   IPER   NOP
0126  00175 175272   PER    DEC -1350
0127  00176 175272   PER1   DEC -1350
0128  00177 177204   PER2   DEC -380
0129  00200 177505   PER3   DEC -187
0130  00201 177776   PER12  DEC -2
0131  00202 177777   PER22  DEC -1
0132  00203 177777   PER32  DEC -1
0133  00204 000000   STE1   NOP
0134  00205 000000   PE2    NOP
0135  00206 000000   ZE2    NOP
0136  00207 000000   STE2   NOP
0137  00210 000000   PE1    NOP
0138  00211 000000   ZE1    NOP
0139  00212 000000   LOOP1  NOP
0140  00213 000000   LOOP2  NOP
```

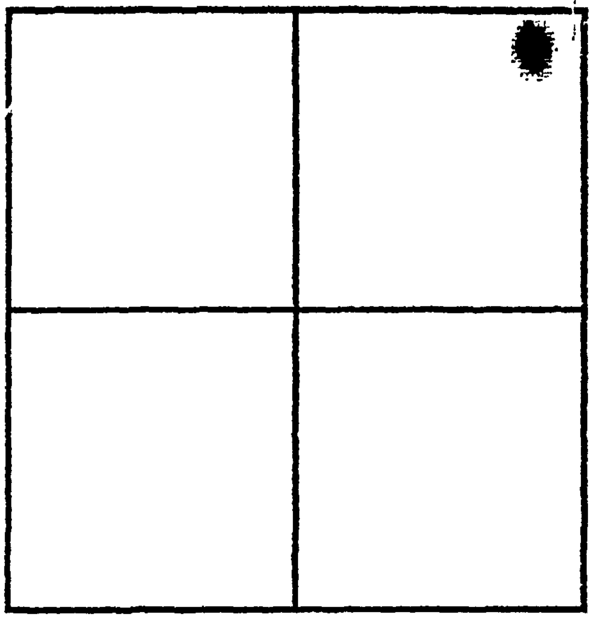
```
      PAGE 0001          FTN4 COMPILER: HP24177  (SEPT. 1974)

            FTN4,L
      C
      C
            SUBROUTINE TRN(A,B,N,M)
      C
      C
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CC                                                                   C
      CC                                                                   C
      CC    THE PURPOSE OF THIS ROUTINE IS TO CREATE THE TRANSPOSE OF THE C
      CC    GIVEN ARRAY (A) AND STORE THE RESULT IN THE OTHER ARRAY (B).  C
      CC                                                                   C
      CC    SOURCE FILE:               TRNS                                C
      CC    OBJECT FILE:               TRNR                                C
      CC    CALLED BY:                 PSEUD                               C
      CC                                                                   C
      CC    A                          REAL ARRAY: DIMENSION N X M: OPERAND C
      CC    B                          REAL ARRAY: DIMENSION M X N: RESULT  C
      CC    N,M                        DIMENSIONS OF ARRAYS AS SPECIFIED ABOVE C
      CC    I,J                        DO LOOP CONTROL VARIABLES           C
      CC                                                                   C
      CC                                                                   C
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      C
      C
            INTEGER I,J,N,M
            REAL A(N,M),B(M,N)
      C
      C
      C     B = TRN [A]
            DO 100 I=1,N
            DO 100 J=1,M
               B(J,I)=A(I,J)
        100 CONTINUE
      C
            RETURN
      C
      C
            END

   ** NO ERRORS**     PROGRAM = 00061        COMMON = 00000

         PAGE 0002  FTN4     FTN4 COMPILER: HP24177  (SEPT. 1974)

            END$
```

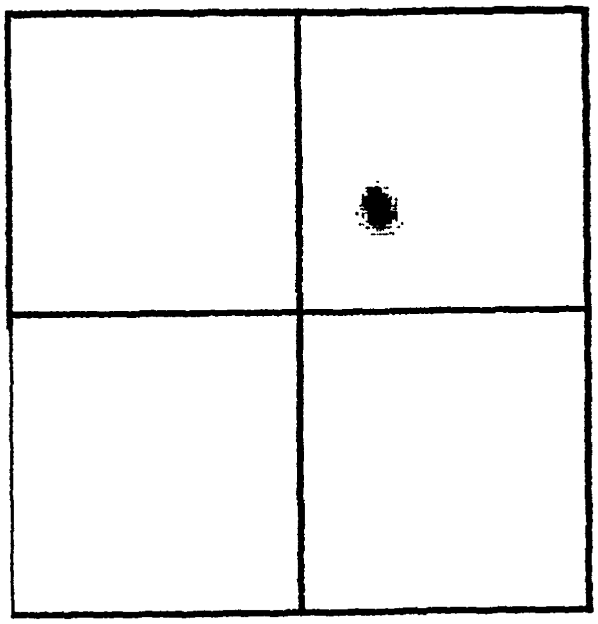
```
          PAGE  0001          FTN4 COMPILER: HP24177  (SEPT. 1974)

              FTN4,L
      C
      C
              SUBROUTINE CLR(A,M,N)
      C
      C
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CC                                                                   CC
      CC                                                                   CC
      CC      THE PURPOSE OF THIS ROUTINE IS TO INITIALIZE A REAL ARRAY    CC
      CC      TO ZERO.                                                     CC
      CC                                                                   CC
      CC      SOURCE FILE:            CLRS                                 CC
      CC      OBJECT FILE:            CLRR                                 CC
      CC      CALLED BY:              MPY                                  CC
      CC                                                                   CC
      CC      A                       REAL DATA ARRAY                      CC
      CC      M & N                   DIMENSIONS OF THE ARRAY              CC
      CC      I & J                   DO LOOP CONTROL VARIABLES            CC
      CC                                                                   CC
      CC                                                                   CC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      C
      C
              INTEGER I,J,M,N
              REAL A(M,N)
      C
      C
              DO 100 I=1,M
              DO 100 J=1,N
                 A(I,J)=0
        100   CONTINUE
      C
              RETURN
      C
      C
              END

  **  NO ERRORS**    PROGRAM = 00054       COMMON = 00000
          PAGE  0002  CLR      FTN4 COMPILER: HP24177  (SEPT. 1974)

              END$
      PAGE 0001           FTN4 COMPILER: HP24177  (SEPT. 1974)
            FTN4,L
      C
      C
            SUBROUTINE MPY(A,B,C,M,N,P)
      C
      C
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CC                                                                    CC
      CC                                                                    CC
      CC    THE PURPOSE OF THIS ROUTINE IS TO PERFORM MATRIX MULTIPLICATION CC
      CC    ON THE FIRST TWO ARRAYS AND STORE THE RESULT IN THE THIRD ARRAY CC
      CC    [MAT C = MAT A * MAT B].                                        CC
      CC                                                                    CC
      CC    SOURCE FILE:             MPYS                                   CC
      CC    OBJECT FILE:             MPYR                                   CC
      CC    CALLED BY:               MAIN                                   CC
      CC                                                                    CC
      CC    A                        REAL ARRAY: 1ST OPERAND: DIMENSION M X N CC
      CC    B                        REAL ARRAY: 2ND OPERAND: DIMENSION N X P CC
      CC    C                        REAL ARRAY: RESULT: DIMENSION M X P    CC
      CC                                                                    CC
      CC    M,N,P                    DIMENSION OF ARRAYS SPECIFIED ABOVE    CC
      CC    I,J,K                    DO LOOP CONTROL VARIABLES              CC
      CC                                                                    CC
      CC                                                                    CC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      C
      C
            INTEGER I,J,K,M,N,P
            REAL A(M,N),B(N,P),C(M,P)
      C
      C
      C     INITIALIZE RESULT
            CALL CLR(C,M,P)
      C
      C     PERFORM MATRIX MULTIPLICATION
            DO 100 K=1,M
            DO 100 I=1,P
            DO 100 J=1,N
                C(K,I)=C(K,I)+A(K,J)*B(J,I)
        100 CONTINUE
      C
            RETURN
      C
      C
            END

  **  NO ERRORS**     PROGRAM = 00102       COMMON = 00000

      PAGE 0002  MPY      FTN4 COMPILER: HP24177  (SEPT. 1974)

            END$
```

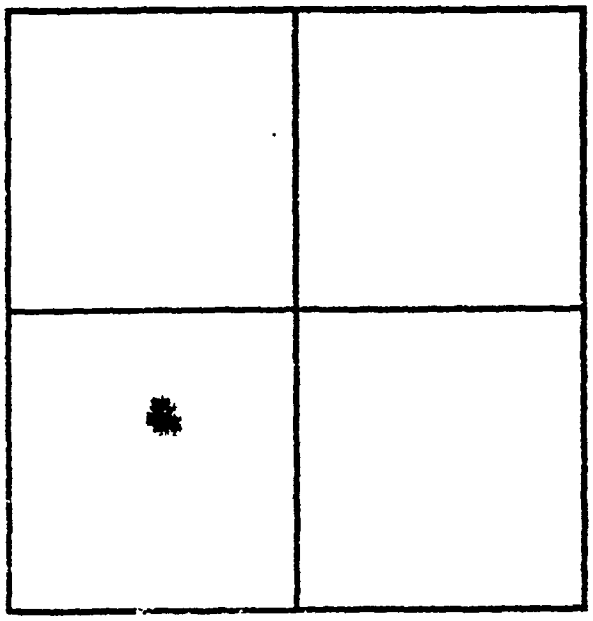
```
PAGE 0001          FTN4 COMPILER: HP24177  (SEPT. 1974)

             FTN4,L
       C
       C
             SUBROUTINE ZER(A,M,N)
       C
       C
       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
       CC                                                                       C
       CC                                                                       C
       CC    THE PURPOSE OF THIS ROUTINE IS TO INITIALIZE AN INTEGER ARRAY      C
       CC    TO ZERO.                                                           C
       CC                                                                       C
       CC    SOURCE FILE:             ZERS                                      C
       CC    OBJECT FILE:             ZERR                                      C
       CC    CALLED BY:               RECT                                      C
       CC                                                                       C
       CC    A                        INTEGER ARRAY                             C
       CC    M & N                    DIMENSIONS OF THE ARRAY                   C
       CC    I & J                    DO LOOP CONTROL VARIABLES                 C
       CC                                                                       C
       CC                                                                       C
       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
       C
       C
             INTEGER I,J,M,N
             INTEGER A(M,N)
       C
       C
             DO 100 I=1,M
             DO 100 J=1,N
                A(I,J)=0
         100 CONTINUE
       C
             RETURN
       C
       C
             END

 ** NO ERRORS**    PROGRAM = 00051       COMMON = 00000

          PAGE 0002  ZER      FTN4 COMPILER: HP24177  (SEPT. 1974)

             END$
```

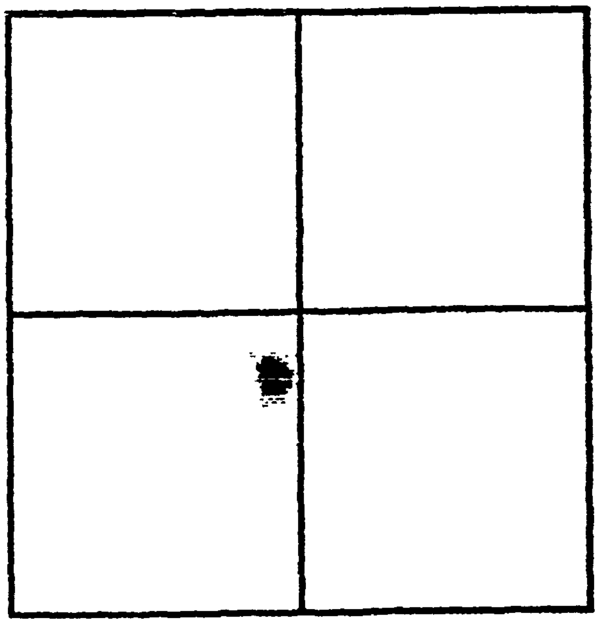
```
      FTN4,L
C
C
      SUBROUTINE SUB(A,B,C,M,N)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC
CC
CC    THE PURPOSE OF THE ROUTINE IS TO GENERATE MATRIX SUBTRACTION
CC    OF THE FORM C = A - B
CC
CC    SOURCE FILE:             SUBS
CC    OBJECT FILE:             SUBR
CC    CALLED BY:               TRACK
CC
CC    A, B, & C                REAL ARRAYS WITH SUPTRACTION DEFINED AS
CC                             FOLLOWS  C = A - B
CC    M & N                    DIMENSIONS OF THE THE ARRAYS
CC    I & J                    DO LOOP CONTROL VARIABLES
CC
CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      INTEGER I,J,K,M,N
      REAL A(M,N),B(M,N),C(M,N)
C
      DO 100 I=1,M
      DO 100 J=1,N
  100 C(I,J)=A(I,J)-B(I,J)
C
      RETURN
C
C
      END

**  NO ERRORS**     PROGRAM = 00075      COMMON = 00000

          PAGE 0002  SUB      FTN4 COMPILER: HP24177  (SEPT. 1974)

      ENDS
```

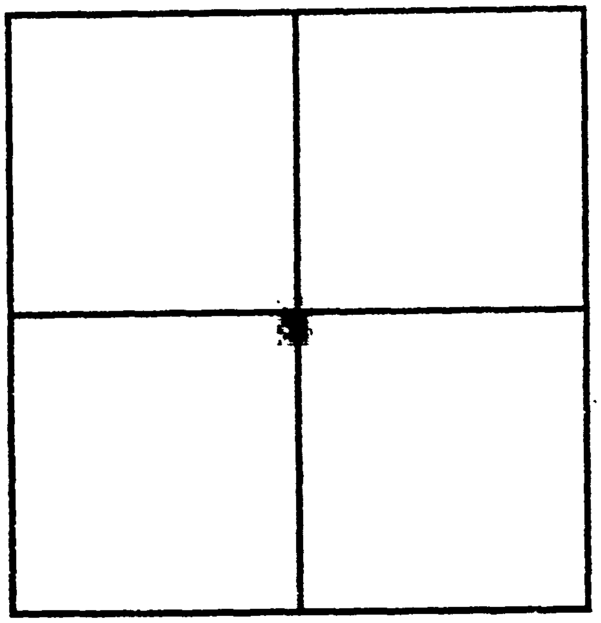
Appendix 2.4: Sequence of Segmented Tracking Scenes

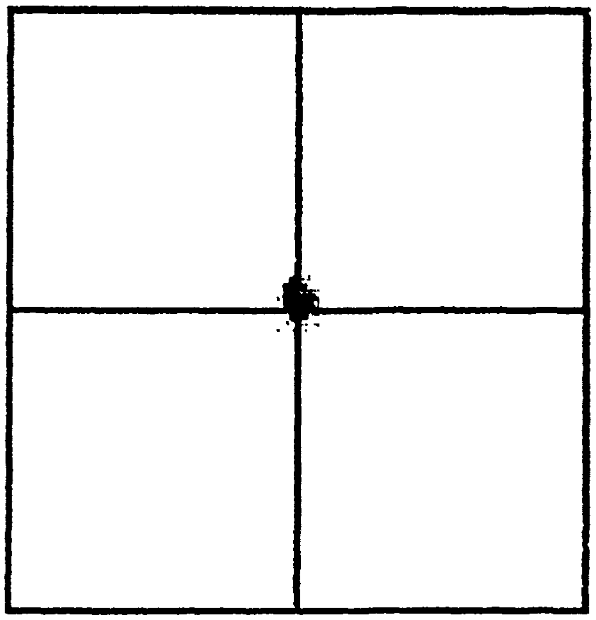


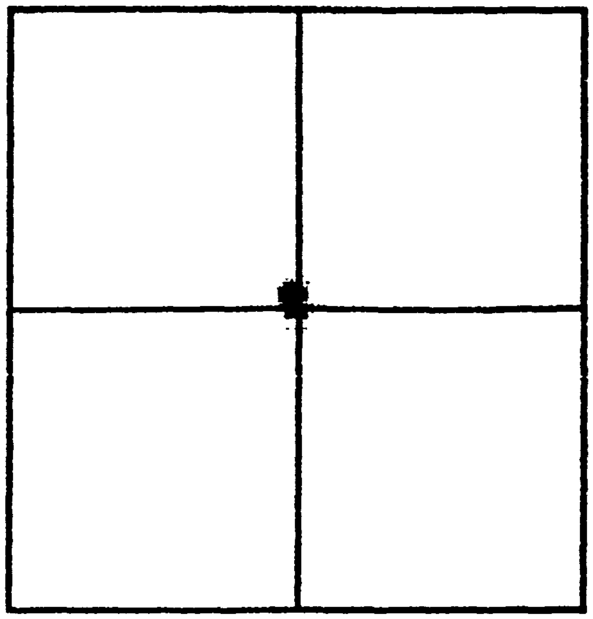


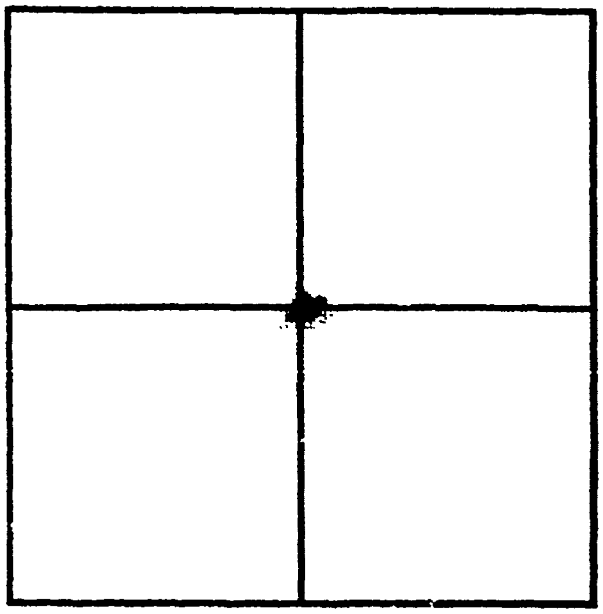




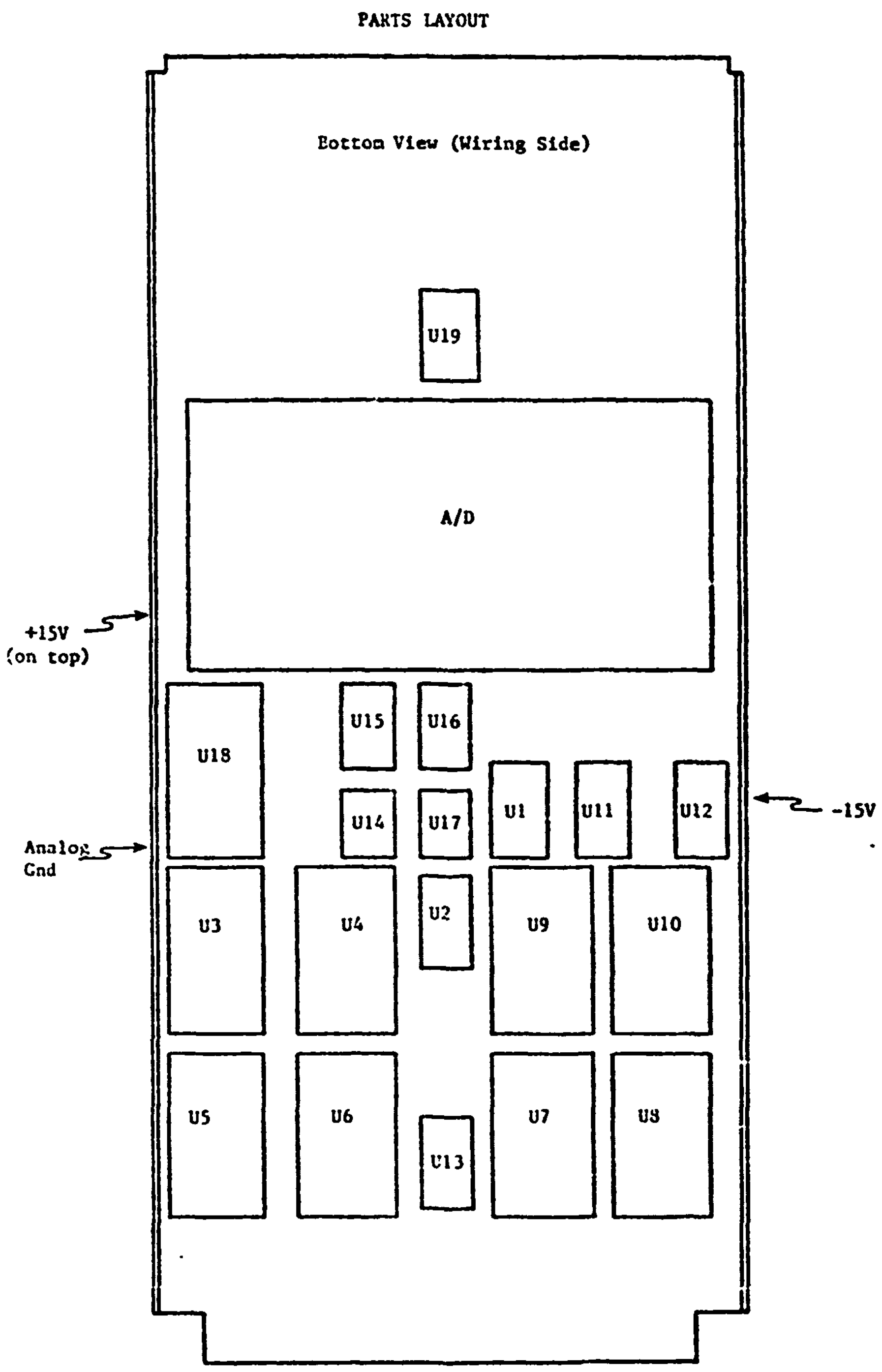








Appendix 2.5: Parts Layout for Video Interface



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